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THESIS

CONNECTION UTILIZATION MASKING IN ATM NETWORKS

by

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13. ABSTRACT *(maximum 200 words)*

A technique for connection utilization masking in ATM networks is presented, modeled, and analyzed. Specifically, a cell injection mechanism is modeled with a two-state Markov Modulated Poisson Process (MMPP) to study its autocorrelation and power spectral density properties and the queue response to the arrival process. The Cruz bound is used to determine injection source traffic parameters. Cell injection is implemented on a permanent virtual channel with a bursty Variable Bit Rate (VBR) source. The result is also VBR traffic having a new set of user-defined statistics. Traffic traces representing before and after injection scenarios are collected and further processed to define autocorrelation and power spectrum density functions. The results are used to compare and justify analytical results. The cell-injected stream shows strong correlation over a long duration, an indication of the removal of burstiness. Cell Transfer Delay, Cell Loss Rate, and Cell inter-arrival time statistics are collected to evaluate injection's effects on Quality of Service (QoS) parameters. Cell injection causes more mid- and high-frequency traffic power to be shifted towards low frequency region in the frequency spectrum, representing an increase in the mean arrival rate.

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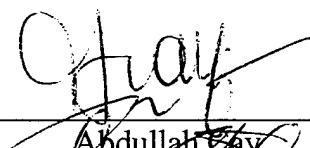
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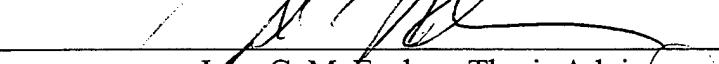
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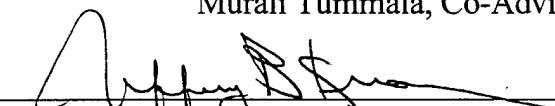
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A technique for connection utilization masking in ATM networks is presented, modeled and analyzed. Specifically, a cell injection mechanism is modeled with a two-state Markov Modulated Poisson Process (MMPP) to study its autocorrelation and power spectral density properties and the queue response to the arrival process. The Cruz bound is used to determine injection source traffic parameters. Cell injection is implemented on a permanent virtual channel with a bursty Variable Bit Rate (VBR) source. The result is also VBR traffic having a new set of user-defined statistics. Traffic traces representing before and after injection scenarios are collected and further processed to define autocorrelation and power spectrum density functions. The results are used to compare and justify analytical results. The cell-injected stream shows strong correlation over a long duration, an indication of the removal of burstiness. Cell Transfer Delay, Cell Loss Rate, and Cell Inter-arrival time statistics are collected to evaluate the injection's effects on Quality of Service (QoS) parameters. Cell injection causes more mid- and high-frequency traffic power to be shifted towards the low frequency region in the frequency spectrum, representing an increase in the mean arrival rate.

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ACRONYMS AND ABBREVIATIONS

ATM	Asynchronous Transfer Mode
CBR	Constant Bit Rate
CDVT	Cell Delay Variation Tolerance
CLP	Cell Loss Priority
CLR	Cell Loss Ratio
cps	Cell Per Second
GCRA	Generic Cell Rate Algorithm
MBS	Maximum Burst Size
Mbps	Megabits Per Second
MMPP	Markov Modulated Poisson Process
NSAP	Network Service Access Point
QoS	Quality of Service
PCR	Peak Cell Rate
PT	Payload Type
PVC	Permanent Virtual Channel
SCR	Sustainable Cell Rate
SVC	Switched Virtual Channel
UPC	Usage Parameter Control
VBR	Variable Bit Rate
VCI	Virtual Channel Identifier
VCC	Virtual Channel Connection
VPI	Virtual Path Identifier

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I. INTRODUCTION

Connection utilization masking is a proactive network security technique for increasing confidentiality in data communications exchanges. This thesis explores a new method for connection utilization masking referred to as "dummy cell injection". Specifically, the effects of cell injection on network timing are analyzed. In light of these observations, cell injection is determined to be a highly effective and flexible means for connection utilization masking.

A.   OVERVIEW

The contributions of this thesis are two fold. First, it provides a theoretical analysis of the cell injection mechanism as modeled by an MMPP. Li and Hwang developed the novel concept of spectral representation of arrival processes in which the relationship between queue response and arrival process input power was studied in [2], [3] and [13]. It was shown that queue performance is dominated by the input power at low frequencies or DC. Using the approach provided in [2] and [12], correlation and power spectrum functions of the model are examined. The effects of cell injection on queue performance are also investigated. In contrast to classical queuing theory that assumes an uncorrelated or independent arrival process, experiments with real applications ([4], [5], [6]) indicate that the arrival process is correlated. The queue response to correlated traffic streams is still under research; however, recently it has been justified that the correlation function of an arrival process reveals the long range dependencies in a stream and effects the cell loss rate in ATM networks.

The second contribution is the implementation of the cell injection using an ADTECH™'s AX/4000 ATM test system in a private ATM network. Cell level parameters , such as cell transfer delay, cell loss ratio, cell inter-arrival time variation of the measured cell stream, are statistically analyzed in order to characterize the effects of dummy cell injection on the original cell stream. Aside from cell level parameters mentioned above, the autocorrelation function and power spectrum of the arrival process are investigated to analyze the effects of the second order statistics of the cell injection mechanism.

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B. MOTIVATION BEHIND CELL INJECTION IN ATM NETWORKS

Traffic analysis is a form of attack on network confidentiality whereby the statistics of the traffic, such as volume, timing, source and destination addresses, and information priority, are collected. Encryption techniques have been developed to secure ATM traffic connections in different scenarios. The two permanent connections, Permanent Virtual Path (VP) and Switched Virtual Paths (SVP), can have Virtual Channel Identifier (VCI) encryption applied. In these types of ATM connection, only the VPI field is modified at every intermediate ATM node throughout the connection while the VCI field remains the same. Therefore, the VCI field is considered to be static. Virtual path encryption is an example of a header encryption technique in which the virtual path fields in the ATM cell header are encrypted. Conversely, if virtual channel switching is employed where both VPI and VCI fields may dynamically change at every node, VCI encryption cannot be applied. Thus, a header encryption approach in addition to payload encryption limits the accessibility of the end user; specifically, an end user trying to establish an SVC connection with another end user will not be successful if VCI encryption is used. Hence, usually only payload encryption is implemented in ATM networks. Payload only encryption leaves the header in clear format for processing in the network or at the end stations.

Despite the above techniques, traffic analysis provides information to an observer even if the payload is encrypted. ATM networks are susceptible to this type of attack because encryption does not affect the volume or timing information, and the source and destination addresses can easily be obtained from the clear cell header and signaling messages. In order to prevent this attack, counter-traffic analysis techniques have been developed. The followings are some examples.

1. Broadcasting

Consider a topology in which military sites forming peer groups are connected via a public ATM-based network. If data from each source is broadcast to every possible end user in the peer groups, then an observer can not distinguish the intended destination from the "dummy" ones. In other words, dummy transmissions will mask the intended connection. Even though the traffic will be measured, the same traffic statistics will be collected for all sites. So, if someone has to classify the connections, both paths and links, based on activity

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level and priority information, it will not be an easy task to do in broadcast type scenarios. Some of the drawbacks with broadcasting are inefficient use of network resources, congestion at some nodes, and difficulty in the implementation as the group size increases.

2. Dummy Cell Injection

Instead of broadcasting, which is described above, utilization and priority information of a connection can still be masked using some of the ATM protocol's foundations. Dummy cell injection is an example based on the idea of utilizing the network resources allocated to a connection more efficiently (e.g., bandwidth and quality of service (QoS) for a connection). As will be discussed further in detail, the physical layer consists of both "assigned" and "unassigned" or idle cells. An unassigned cell, or idle cell, is basically a placeholder that has a standard header format. Assuming unassigned cells are used, the cell injection mechanism replaces them with predetermined assigned ones. After injecting cells, the connection utilization will stabilize around a fixed value, usually the average cell rate.

The ATM protocol layer provides for the transport of fixed size ATM layer service data units (ATM-SDU) between communicating upper layer entities (e.g., AAL entities). This transfer occurs on a pre-established ATM connection according to a traffic contract. A traffic contract consists of a Quality of Service (QoS) class, a vector of traffic parameters, and a conformance definition. Each ATM end point is expected to generate traffic that conforms to the QoS parameters. Table 1.1 shows the ATM layer functions that need to be supported at the User Network Interface (UNI). [1]

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Functions	Parameters
Multiplexing among different ATM connections	VPI/VCI
Cell Rate Coupling (Unassigned Cells)	Pre-assigned header field values
Cell discrimination based on predefined header field values	Pre-assigned header field values
Payload Type discrimination	PT field
Loss Priority indication and Selective cell discarding	CLP field, Network congestion state
Traffic Shaping	Traffic descriptor

Table 1.1 Functions Supported at the UNI (U-plane). [1]

Due to its relevance to the cell injection mechanism, cell rate coupling is considered important and needs to be explained in detail. As mentioned earlier, the cell rate coupling function at the sending entity (e.g., ATM switches) adds "unassigned or idle" cells to the assigned cell stream transforming a non-continuous stream of assigned cells into a continuous one. At the receiving end, a reverse operation is done in which the unassigned cells are discarded and valid cells are passed to upper layers. The rate at which the unassigned cells are inserted/extracted depends on the physical layer's transmission rate. The assigned and unassigned cells are recognized by specific header patterns as shown in

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Table 1.2. As seen from the table, the default VPI/VCI pair values for unassigned cells are VPI = 0 and VCI = 0.

Physical layer media that have synchronous cell time slots generally require cell rate coupling (e.g., SONET, DS3) whereas physical layer media with asynchronous cell time slots do not need coupling because no continuous cell stream is required. Therefore, if the physical layer requires a continuous cell stream, equipment supporting the UNI, such as an ATM switch, generates unassigned cells in the flow of cells passed to the physical layer to match the link capacity.

USE	Value			
	Octet 1	Octet 2	Octet 3	Octet 4
Unassigned Cell Indication	00000000	00000000	00000000	0000xxx0
General Broadcast Signaling	0000yyyy	yyyy0000	00000000	00100aac
Point-to-Point Signaling	0000yyyy	yyyy0000	00000000	01010aac
Invalid Pattern	xxxx0000	00000000	00000000	0000xx1

1: "a" indicates that the bit is available for use by the appropriate ATM layer

 function

2: "x" indicates do not care bit

3: "y" indicates any VPI value other than 00000000

4: "c" indicates that the originating signaling entity shall set the CLP bit to zero.

 The network may change the value of the CLP bit.

Table 1.2 Pre-defined Header Values [1].

The cell injection mechanism examined in this thesis is based on replacing these unassigned cells with the ones having a predetermined payload and the same header fields as valid cells so that the volume and timing of the valid traffic will effectively be hidden. As mentioned earlier, even over encrypted connections, header fields are generally passed in the clear. This still allows an eavesdropper to classify the captured cells based on their VPI/VCI pair, discriminate the cells using Payload Type Field (PT), and identify the priority of the cells by using Cell Loss Priority (CLP) field in the header. Cell injection, however, will mitigate any further inference on the nature of the information being passed. Consider the simple case of VPI that has only one VCI used for user traffic connections. If the dummy cell injected stream is captured, it will look like an almost constant flow having some variance of cells with the same VPI/VCI field values. After encryption, the valid and dummy data will be undistinguishable to the eavesdropper.

C.   THESIS ORGANIZATION

This thesis is organized as follows. Chapter II provides an overview of the relevant aspects of ATM. Chapter III discusses the theoretical aspects of the cell injection mechanism. The mechanism is modeled with a two-state MMPP. Using the theories provided in [2], the autocorrelation and power spectrum of the original and aggregate traffic will be determined. Chapter IV presents both the features of the private ATM network over which different traffic streams are simulated and the basic features of ADTECH™'s AX/4000 ATM test system. The AX/4000 ATM test system is used to generate and capture different traffic types. The cell injection source model and cell level measurements along with statistical analysis, correlation function and power spectrum, are provided and discussed in Chapter V. Chapter VI concludes the thesis with a summary and possible future work on the same topic.

II. ATM OVERVIEW

A.   BACKGROUND

Asynchronous Transfer Mode (ATM) is a connection oriented multiplexing and switching technology in which the data is segmented into small fixed length packets called cells. The goal of ATM is to integrate and provide transport services for a wide variety of traffic, such as data, voice and video, and Quality of Service (QoS) based on traffic types. ATM delivers important advantages over existing LAN and WAN technologies including the following:

- Minimizes the switching complexity

- Simplifies Network Management

- Minimizes the processing time at the intermediate nodes which yields to a minimized packetization and depacketization delay

- Utilizes the network resources efficiently

- Supports existing as well as emerging service types and QoS guarantees

The ATM architecture is based on the Broadband-ISDN reference model shown in Figure 2.1. It includes management, control and user planes for three unique layers: the ATM adaptation layer (AAL), ATM layer and physical layer. The user plane (U-plane) provides for the transport of user data, whereas the control plane (C-plane) provides for signaling and control functions. The management plane enables the user and control planes to work together through the use of a variety of feedback messages.

The ATM adaptation layer assures the appropriate service characteristics and maps all types of higher layer data into the ATM layer. Due to the multiplexing of different applications in ATM networks, more than one service class and ATM adaptation layer (AAL) has been defined to support them. The AAL consists of two sub layers: the Convergence (CS) and the Segmentation and Re-assembly sub layer (SAR). The CS performs functions like padding header and trailer to the frames, loss detection and other service dependent functions. SAR is responsible for segmenting user data into 48 bytes of

payload and reassembling the incoming cells to form higher layer data. The AAL service classifications are shown in Table 2.1.
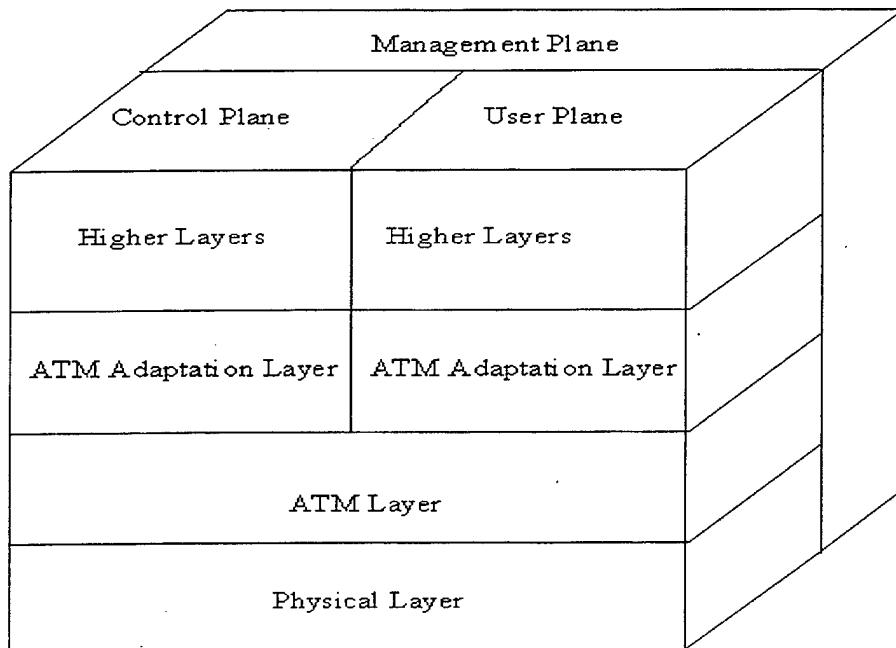
Figure 2.1 B-ISDN Reference Model [1].

Criteria	Class A	Class B	Class C	Class D	Class X
Timing between source and destination	Required	Required	Not required	Not required	User defined
Bit Rate	Constant	Variable	Variable	Variable	User defined
Connection Mode	Connection-Oriented	Connection-Oriented	Connection-Oriented	Connectionless	Connection-Oriented
AAL type	AAL1	AAL2	AAL3/4 and 5	AAL3/4 and 5	AAL0

Table 2.1 AAL Service Classifications [7].

The ATM layer is responsible for flow control, header generation, multiplexing/demultiplexing of cell streams, and label swapping.

The physical layer defines the electrical characteristics and network interfaces [7]. It consists of two sub layers: Physical medium dependent (PMD) and Transmission Convergence (TC). The PMD sub layer performs insertion and extraction of bit timing and any necessary line coding. The TC is responsible for cell delineation, header error check operations and mapping and re-mapping of cells to a transmission frame (e.g., SONET, DS-3 etc.). Of all the physical layer options that ATM can operate over, SONET is the most preferable due to the fact that SONET can provide the high data rates ATM requires.

B.   CELL STRUCTURE AND CONNECTION TYPES

1.   Cell Structure

An ATM network may have a set of ATM switches connected by point-to-point ATM links or interfaces. These interfaces define a set of protocols and traffic characteristics, (e.g., cell structure) between either two network nodes or a host and a network node. ATM switches support two types of interfaces: User-to-Network Interface (UNI) and Network-to-Network Interface (NNI). The UNI connects hosts, routers, etc. to an ATM switch, while an NNI connects two ATM switches. These ATM interfaces are depicted in Figure 2.2.

As mentioned earlier, fixed length cells are employed for the transport of data. An ATM cell is 53 bytes in length. It is divided into two parts: a five-byte header and a 48-byte payload. The ATM Forum, an industry-academic consortium standards group, has defined two header formats. Figure 2.3 shows structure of an UNI ATM cell format. In NNI cells, unlike UNI cells, there isn't a generic flow control (GFC) field. The first four bits are used instead to extend the VPI field.

The header provides control protocol information to the ATM layer to identify cells belonging to the same virtual channel. UNI ATM cell contains the following fields:
Generic Flow Control (GFC): This field has local significance only and can be used to provide flow control on the customer equipment side.
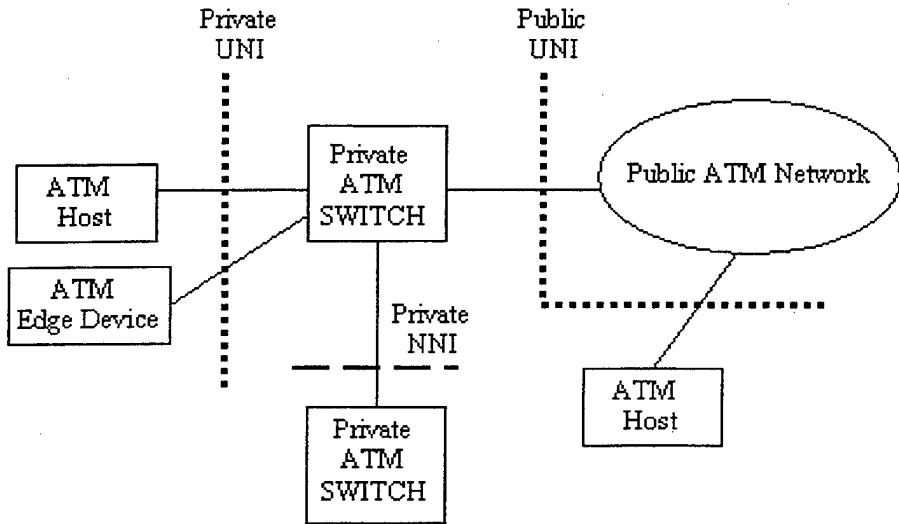
Figure 2.2 ATM Interfaces After Ref. [7]:p. 148

Virtual Path/Virtual Channel Identifiers (VPI/VCI): The VPI/VCI fields are connection identifiers used in cell routing through an ATM network. A VPI/VCI pair identifies a virtual circuit.

Payload Type (PT): The PT field is used to indicate the data type contained in the payload, (e.g., user data or connection associated layer management information such as F5 flow). It is also used for network resource management and to indicate a network congestion state.

 Cell Loss Priority (CLP): The CLP bit indicates the explicit loss priority of the cell. It identifies whether a cell is compliant with the traffic contract or not. A CLP=0 value defines high priority whereas CLP=1 low priority. In case of network congestion low priority cells are discarded.

Header Error Control (HEC): The HEC field is used by the physical layer for detection/correction of bit errors in the header.

```
        MSB                          LSB

        7    ..........   4   . . .   0

   ┌────────────────┬────────────────┐ ⎞
   │      GFC       │      VPI        │ ⎟
   ├────────────────┼────────────────┤ ⎟
   │      VPI       │      VCI        │ ⎟
   ├────────────────┴────────────────┤ ⎟
   │              VCI                 │ ⎬  5 Octects
   ├──────────────┬─────┬────────────┤ ⎟
   │     VCI      │ PT  │    CLP      │ ⎟
   ├──────────────┴─────┴────────────┤ ⎟
   │              HEC                 │ ⎠
   ├──────────────────────────────────┤ ⎞
   │                                  │ ⎬  48  Octects
   │            Payload               │ ⎟
   │                                  │ ⎠
   └──────────────────────────────────┘
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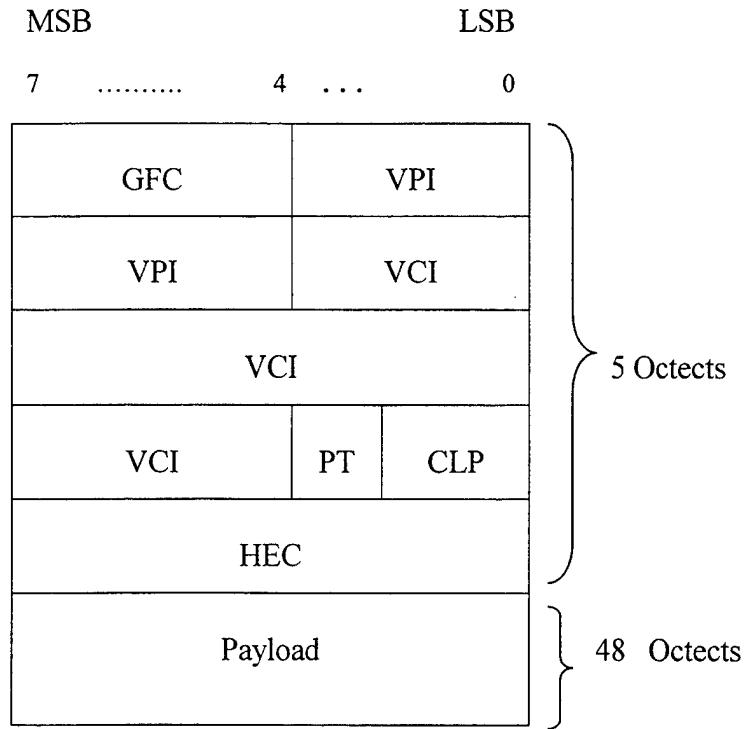
Figure 2.3 UNI ATM Cell Structure.

2.   Virtual Paths and Virtual Channels

ATM networks are described as connection oriented because a logical channel between two ATM end users is required to transport cells. This end-to-end logical connection is called virtual channel connection (VCC), which is a concatenation of one or more virtual channels. The logical connection remains the same during the connection period allowing the end system to receive cells in sequence. There are two basic ATM circuit types: Virtual Paths, identified by a Virtual Path Identifier (VPI) and Virtual Channels, identified by a VPI and a Virtual Channel Identifier (VCI). The VPI and VCI may be remapped to other values as the cells traverse through to switches; hence their significance is local in nature.

A virtual channel describes the unidirectional transport of ATM cells with a common VCI value in each cell. The virtual path is a group of virtual channels. Figure 2.4 illustrates the relationship between them. Each VC is associated with a VP. Multiple VCs can be associated with the same VP. [7]
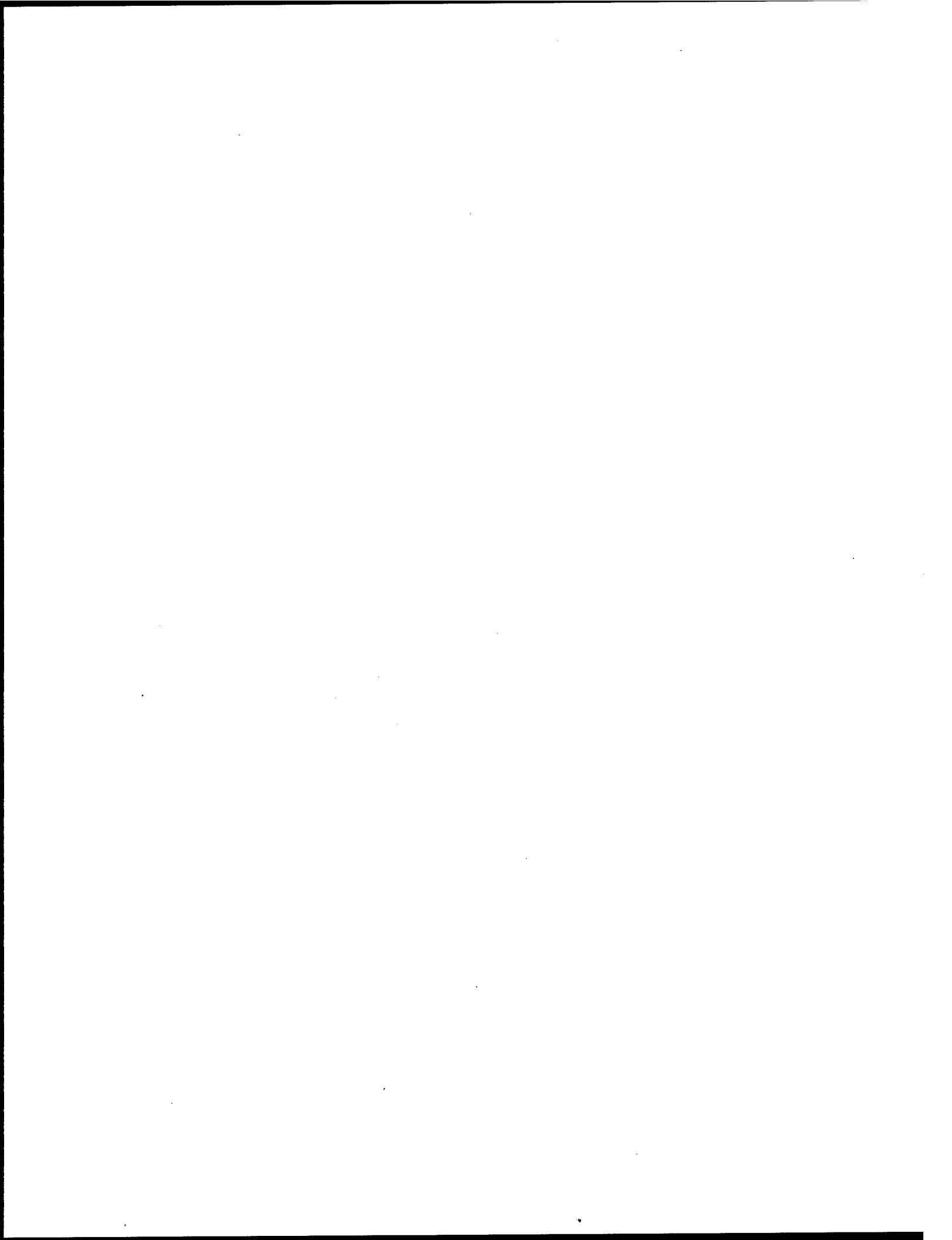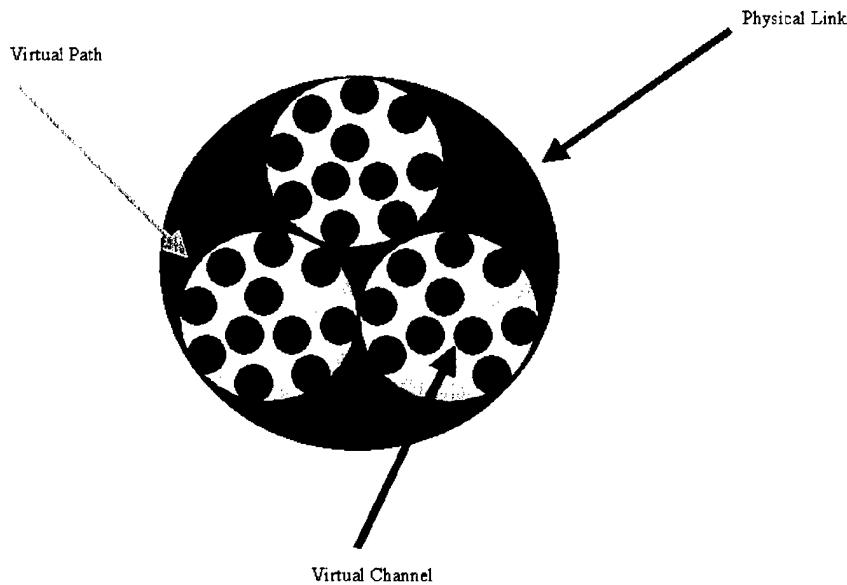
Figure 2.4 VP and VC in the Transport Path [8].

3. Cell Routing and ATM Connections

a) *Cell Routing*

The routing of cells over an ATM network is very similar to the *label-swapping* concept of packet switching technologies such as X.25 and frame relay. The concept can be explained as follows. Each cell contains a logical connection identifier (LCI). At each node the cell LCI and the input port are mapped to a new LCI and an output port. This process continues until the cell reaches its destination [7]. In ATM networks, the ATM switch using the concept described above carries out the required routing function. The basic function of an ATM switch is to map incoming cells received at a specific input port to an outgoing port with a new set of connection identifiers (VPI/VCI) via a table lookup operation. The contents of the routing table may be filled in either manually or by signaling. Figure 2.5 illustrates the basic routing operation in an ATM switch.

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INPUT		OUTPUT	
Port	VPI/VCI	Port	VPI/VCI
1	0/123	2	0/113
1	0/114	3	1/115
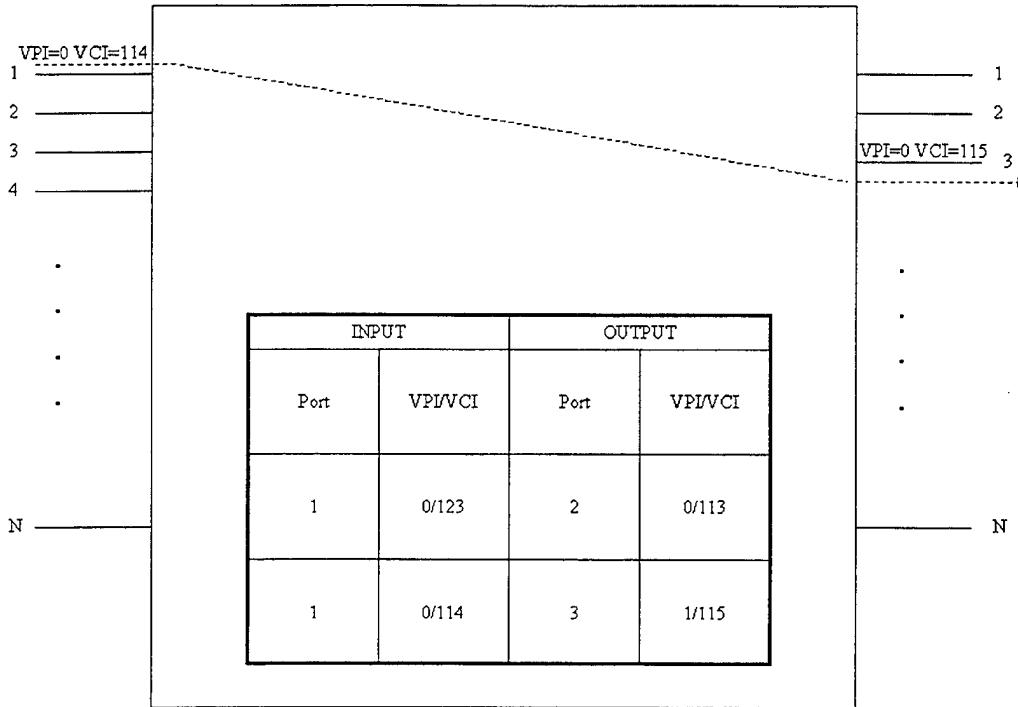
Figure 2.5 ATM Switch. After Ref. [9]:p. 182

The routing table contents consist of two types of end-to-end connections: Permanent virtual connections (PVC) and Switched virtual connections (SVC). A PVC is a manually configured connection in which a set of switches between the source and destination are manually programmed with appropriate VPI/VCI values. On the other hand, an SVC is a connection that is set up automatically through a signaling protocol. The signaling is routed through the network from switch to switch, setting up the connection identifiers as it goes, until it reaches the end system [7]. In the case of link outages SCVs can find alternate routes making them more robust than PVCs. SVCs remain active only for the duration of the data transfer and would not be re-established after a failure. In contrast PVCs are set up and cleared via provisioning and may be re-established.

Since the routing mechanism solely depends on the connection identifiers, two levels of switching can be performed: VP and VP/VC switching. Figure 2.6 (a) is an example of VP/VC switching where both the VPs and VCIs are mapped to new ones. From the figure we can see that in a VP/VC switch, VP/VC values must be first terminated and

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then originated again. In contrast, Figure 2.6 (b) shows VP switching in which the VCIs are unaltered.
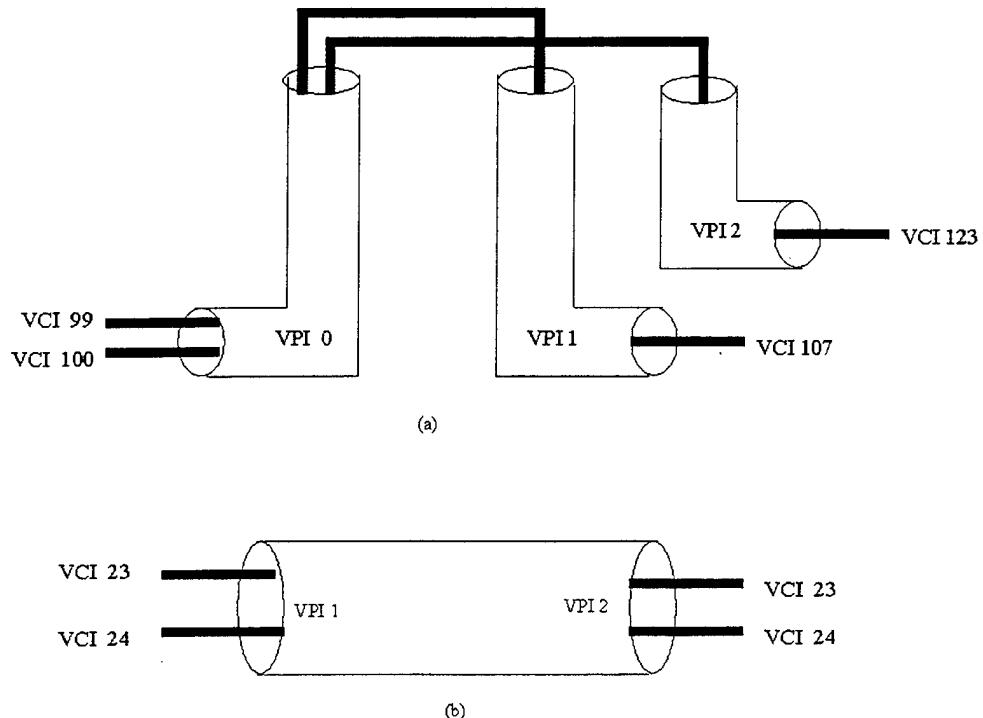
Figure 2.6 VP and VC Switching [10].

b)   *ATM Signaling and Connection Set up*

The ATM signaling is a protocol designed to establish and clear SVCs between two end users by exchanging messages including set up, maintain and clear. The signaling messages are sent in cell format over a standard signaling channel, VPI = 0 and VCI = 5, defined by ATM forum. In order to establish a connection, the end user must have a unique 20-byte ATM address. This address is obtained automatically by using the SNMP-based Interim Local Management Interface (ILMI) protocol. ILMI messages are also carried over a specified channel, VPI = 0 and VCI = 16. Figure 2.7 depicts the exchange of address information and the registration procedure between a switch supporting ILMI and a user.

During the connection set up shown in Figure 2.8, the end user provides the called end system ATM address'; it's ATM address, forward and backward bandwidth requirements, end-to-end delay and QoS parameters for the connection via a signaling

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message. The end system will either accept the call or reject it. The decision will be based on traffic control functions, which will be described in the next section.
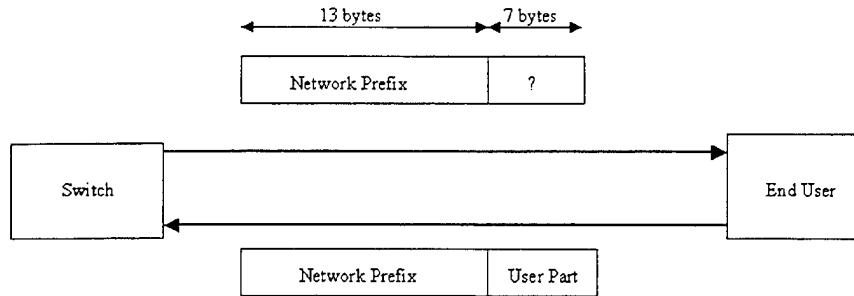
Figure 2.7 Address Registrations.
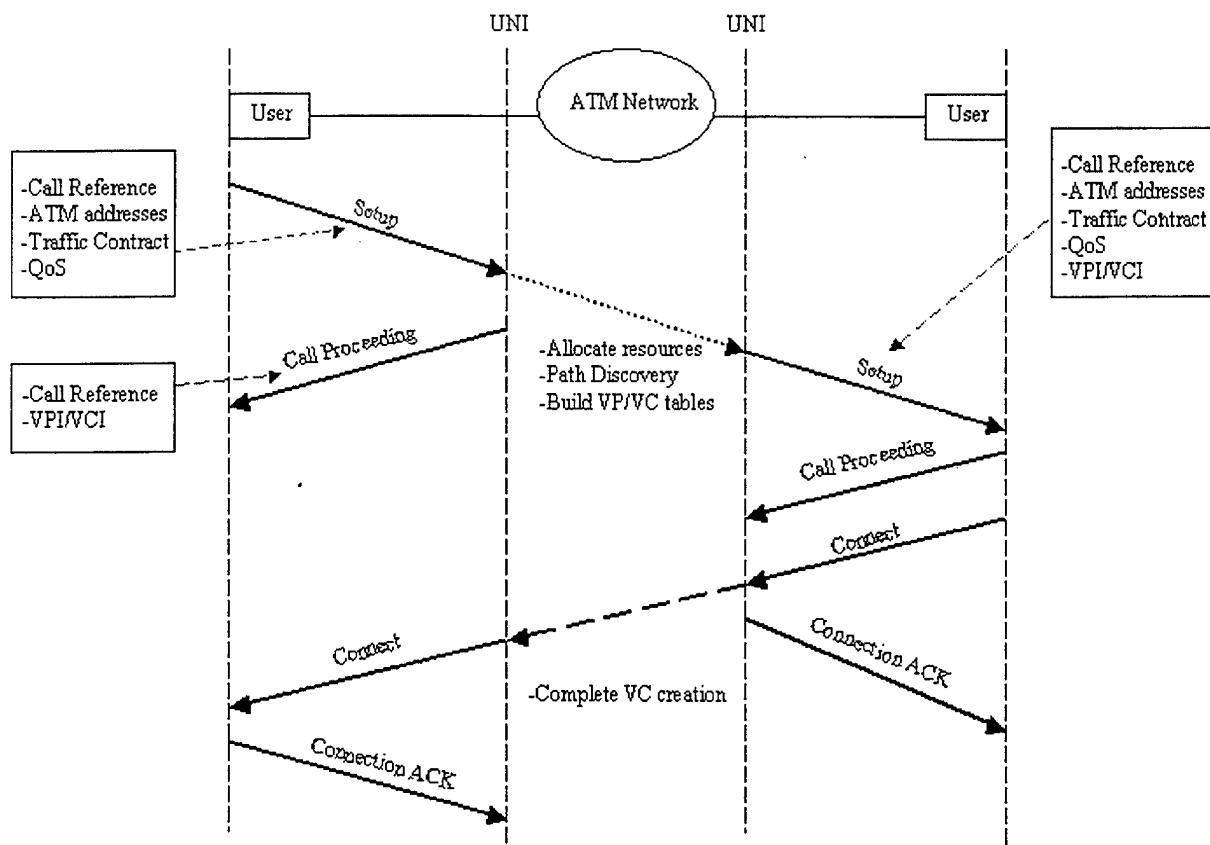
Figure 2.8 Connection Setup [10].

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C.   TRAFFIC MANAGEMENT

1.   Traffic Control and Congestion Control

The ATM forum has defined a service architecture with five previously defined and one newly developed ATM layer service categories that relate traffic and QoS parameters to network behavior.

They are:

- Constant Bit Rate (CBR)
- Real time variable bit rate (rt-VBR)
- Non-real time variable bit rate (nrt-VBR)
- Available bit rate (ABR)
- Unspecified bit rate (UBR)
- Guaranteed Frame Rate (GFR)

As discussed before, ATM integrates different types of applications, which have different characteristics and traffic requirements. Therefore, the aggregate traffic is random in nature. To ensure that limited network resources are allocated fairly and QoS objectives, which are defined by a set of parameters such as cell delay variation, cell transfer delay, cell loss ratio etc. are met for both existing and new connections, a set of traffic management functions are defined. Traffic management has two parts: Traffic control and congestion control. In [1], the congestion is defined as a state of network elements (e.g., switches, transmission links etc.) in which the network is not able to meet the negotiated network performance objectives. The primary goal of traffic control is to avoid congestion, while congestion control tries to prevent sources' exceeding the available resources and minimize the congestion. These controls are mostly implemented at the UNI, the network entry points. Common implementations include the following:

a)   Connection Based Control

This control takes place during call set-up time in order to determine whether to accept or reject a request. It is known as connection admission control (CAC).

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b)   *Cell Based Control*

This control is based on monitoring and controlling the traffic in terms of traffic offered and its conformance. The main goal is to prevent violations, which may affect the QoS of existing connections. Some typical implementations are: Usage parameter control (UPC), generally known, as "traffic policing", Priority Control, and Traffic Shaping. The two cell based traffic control functions, UPC and traffic shaping, are application dependent user-defined functions. The network performance for specific traffic types depends on how a network operator defines them in the ATM switch configuration files. Specifically,

- UPC is defined in [1] as set of actions taken by the network to monitor and control traffic in terms of traffic offered and validity of the ATM connection. The cells violating the contract will either be discarded or tagged depending on the contract definition. The UPC is performed at the network ingress switches and can be implemented at both the VP and VC levels.

- Traffic shaping is a mechanism used to change the traffic characteristics to prevent possible future congestion in the network and thus achieve better network efficiency. Some examples are: PCR reduction, traffic burst smoothing, and reduction of cell clumping by buffering. It can be implemented anywhere in the network. For example, when located at the network ingress, traffic shaping will smooth out the traffic by reducing the PCR, and CDV.

c)   *Feedback Based control*

This control is used in congestion control mechanisms to minimize the congestion by regulating the source transmission rate depending upon the destination network's congestion state.

2.   User-Network Traffic Contract

A Traffic contract is defined as an implicit agreement between the ATM end user and the network, which includes *connection traffic descriptors, a requested QoS class,* and *a conformance definition [1]*. The traffic contract concept is shown in Figure 2.9.

The call confirmation message values are user defined traffic descriptor values stored in tables for each virtual channel. During virtual channel definition, the network operator assigns these values.

a) *Traffic Parameters and Descriptors*

Traffic parameters describe a particular characteristic of a connection. They may define peak cell rate, sustainable cell rate, maximum burst size, and minimum cell rate. A brief definition for each parameter is provided next.

- Peak Cell Rate: An upper bound on the traffic that can be submitted on a connection (e.g., 353,207 cells/sec for OC-3 and 1,416,906 cells/sec for OC-12). It can also be defined as the inverse of minimum cell inter-arrival time at the physical layer service access point (SAP).
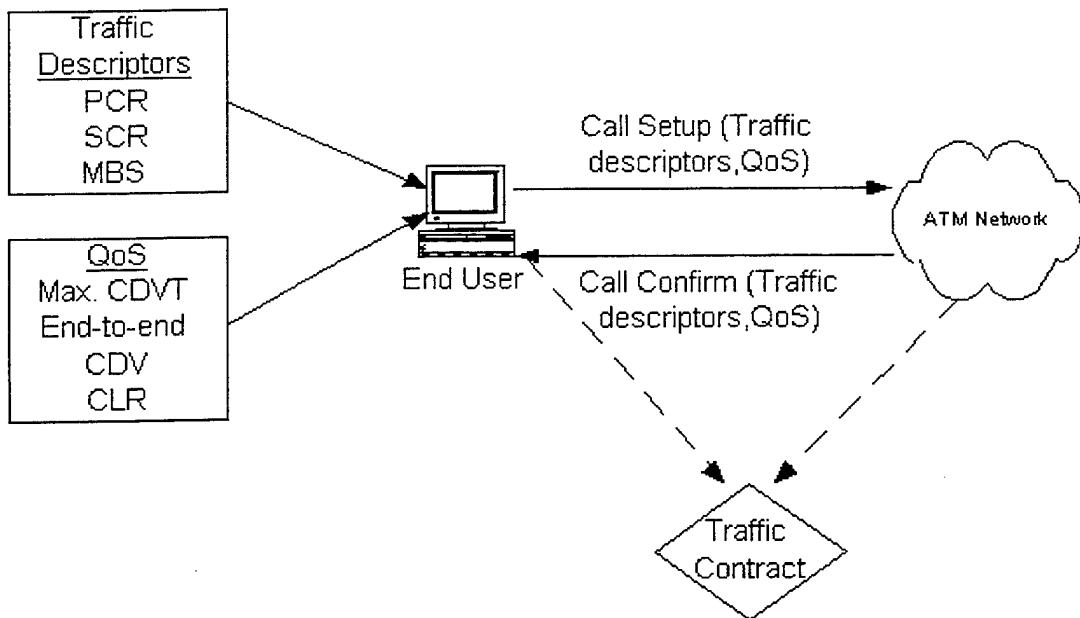

Figure 2.9 Traffic Contract Concept After Ref. [7]:p. 199

- Sustainable cell rate: An upper bound on the conforming average of an ATM connection.

- Maximum burst size: The amount of time that a connection can accept traffic at the peak cell rate.

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- Minimum cell rate: The minimum cell rate that the network can provide for a connection.

ATM traffic descriptors and parameters have the same meaning. A *source traffic* descriptor is a set of traffic descriptors used in the connection set up phase to define characteristics of the requested connection. The *connection traffic descriptor* defines the characteristics of the ATM connection at the public or private UNI [1]. It includes source traffic descriptor, the cell delay variation tolerance (CDVT) and the conformance definition. Connection Admission Control (CAC) functions use the connection traffic descriptor both to determine whether to accept a call and also to derive necessary values for the operation of the UPC.

The CDVT is a measure of variation in the cell inter-arrival times. Queuing or delays due to cell multiplexing process at the switches from OAM cells or other user cell insertions may delay the cells of a given connection. The CDVT represents an upper bound on the variation. A too big variation could cause problems known as cell clumping which may result in cell losses at the node.

b) Conformance Definition

The conformance definition is a type of test applied to the cells as they pass through the UNI to specify if they are conforming or not with the contract. The conformance definition test is based on a continuous state Leaky Bucket algorithm (a category of virtual scheduling algorithm) known as the Generic Cell Rate Algorithm (GCRA). The Leaky bucket could be depicted as a bucket with a fixed-size hole at the bottom, draining at a constant speed as shown in Figure 2.10. As cells arrive, they're added to the bucket. If there is an overflow, those cells are regarded as non-compliant and either tagged or dropped.

The GCRA is used to define the relationship between PCR and CDVT and the relationship between SCR and Burst tolerance. It has two parameters: the increment I and the limit L. The generic notation for peak cell rate conformance definition is GCRA (I, L). The parameters I and L are equivalent to peak emission interval T, which is equal to T=1/PCR, and CDVT respectively. For each conforming cell, a theoretical arrival time (TAT) is calculated for the next cell simply by incrementing actual arrival time by I. If the

actual arrival time of the next cell is less than TAT-L, the cell is considered as nonconforming. More information on GCRA algorithm can be found in [1].

Different combinations can be applied to the same connection depending on the traffic as illustrated in Figure 2.11. For example, the conformance definition for rt-VBR uses a dual leaky bucket GCRA: one for GCRA (1/ PCR, CDVT) and one for GCRA (1/SCR, BT).
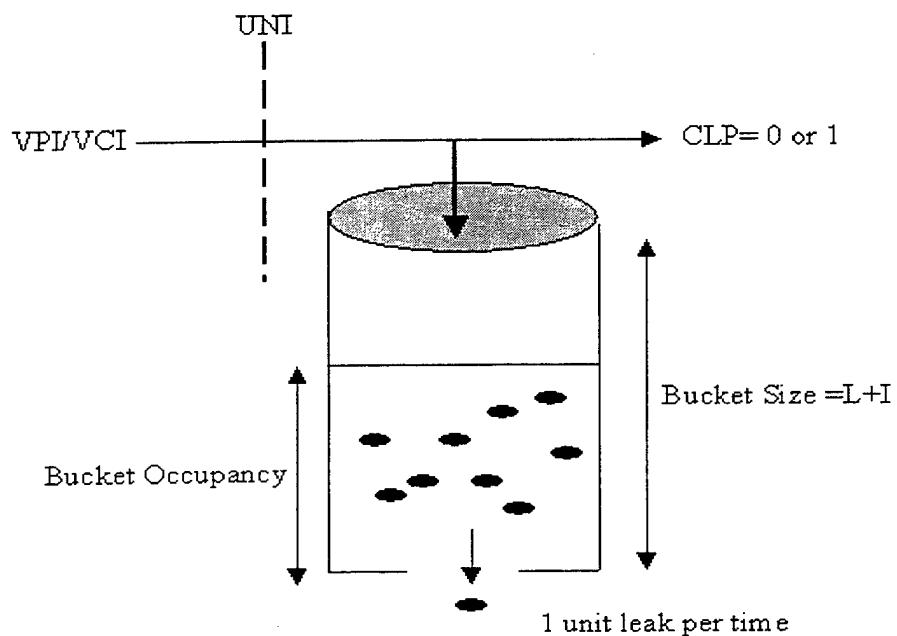
Figure 2.10 Reference Model for GCRA. After Ref. [10]:p. 230
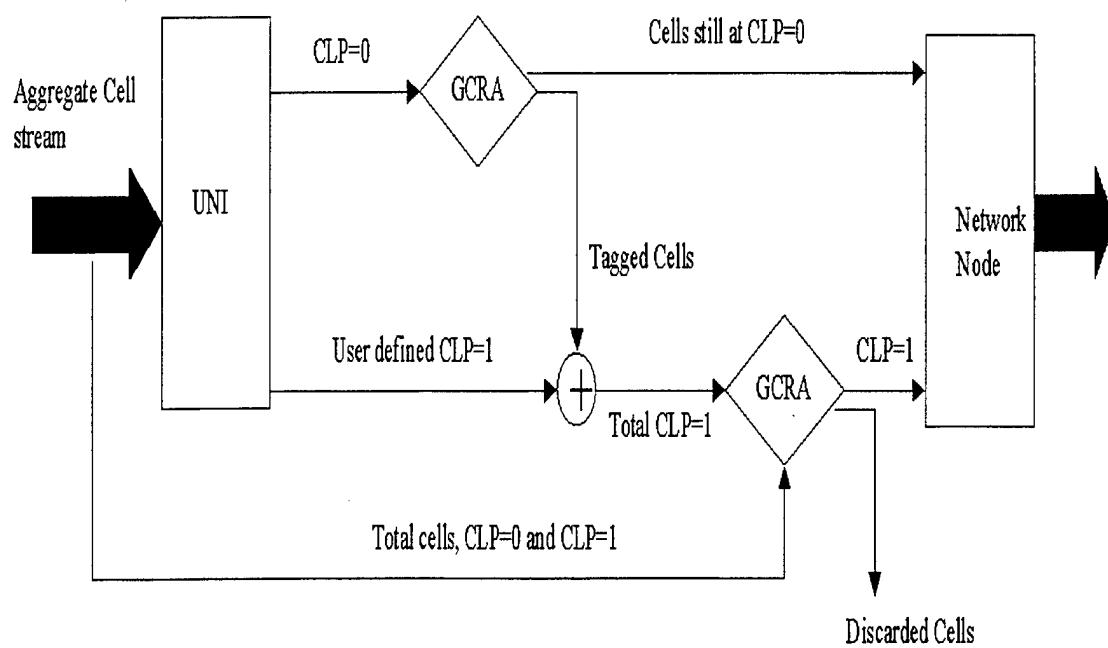
Figure 2.11 Dual Leaky Bucket GCRA [10].

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III. CELL INJECTION MODELING AND STATISTICAL ANALYSIS OF ATM TRAFFIC

A.   CELL INJECTING SOURCE MODEL

Each video, voice or data connection over ATM may have different bandwidth allocations. It was discussed in Chapter II that the traffic contract includes parameters PCR, SCR and MBS that need to be specifically defined before the data transfer occurs. The traffic contract specifies the flow of ATM traffic. Therefore, these are the most important parameters for one who wants to alter traffic characteristics. Of these three parameters, CBR requires PCR, and VBR requires PCR, SCR and MBS to be explicitly defined.

Bandwidth for a CBR connection is fixed at the PCR for the duration of the connection. Because the source could transmit at a cell rate less than the assigned PCR, some of the bandwidth will be wasted as depicted in Figure 3.1.
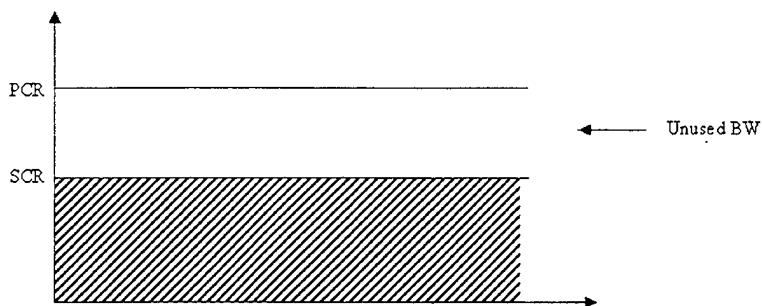
Figure 3.1 CBR Bandwidth Usage.

VBR services are defined for applications whose bandwidth requirements fluctuate during the connection because of the underlying compression schemes used in the application. VBR traffic flow is characterized by all three parameters: PCR, SCR and MBS. The source is assigned an average cell rate in the SCR, but may temporarily send at a maximum cell rate as defined in the PCR for a period of time not to exceed the MBS. A VBR connection's bandwidth usage is illustrated in Figure 3.2.

This unused bandwidth has two primary disadvantages. First, the user is underutilizing the allocated network resources that he is paying for. Second, traffic analysis can easily provide insight into the users' traffic patterns because assigned cells can easily be differentiated from the unassigned cells. A method to overcome these disadvantages is cell injection.

Cell injection is based on the idea of filling up the unassigned cell slots in each physical layer frame so that the allocated bandwidth and resources will be maximally utilized. The injection process is totally under user control in the sense that whenever the user application requires bandwidth, the injection is halted. It is reactivated during intervals when the available cell slots are used by filler cells.
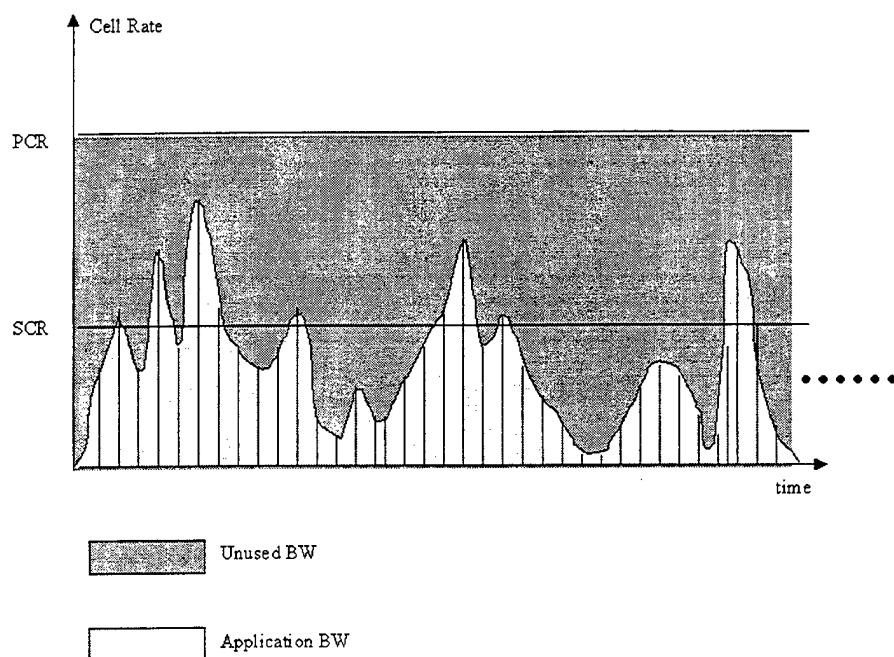
Figure 3.2 VBR Applications Bandwidth Usage.

The essence of cell injection lies in the modification of user traffic characteristics. The user application traffic has a certain mean and variance, which reveals its characteristics. From a statistical analysis point of view, cell injection can be interpreted as the addition of two random stationary processes where each random process has a certain mean and variance. The statistics of the resultant process is determined by the statistics of

the individual processes. In other words, its mean and variance depend upon the mean and variance of the individual sources.

Therefore possible applications can include the following:

- VBR-to-VBR (Variance and Mean Modification)

- CBR-to-CBR (Mean Modification)

- CBR-to-VBR (Variance and Mean Modification)

In determining the mean and variance of the random processes both the long-term source statistics and channel statistics must be considered. Simply, the mean and variance of the aggregate traffic must be upper bounded by those of the channels. Otherwise, if the cell injection causes the aggregate stream to exceed a certain threshold QoS, degradation for user traffic will be inevitable. These bounds will be discussed next.

Let $G(t)$ be the instantaneous rate of a connection at time t; the traffic generated by the source during an interval is given in [11] by

$$A(t_1,t_2) = \int_{t_1}^{t_2} G(t)dt \leq \sigma + \rho(t_2 - t_1) \tag{3.1}$$

where σ is the burst size and ρ is the long-term average rate of the traffic. Hence, as $t_2 - t_1 \rightarrow \infty$

$$\lim_{t_2-t_1 \rightarrow \infty} \frac{A(t_1,t_2)}{t_2 - t_1} \leq \rho . \tag{3.2}$$

An intuitive explanation of the above is as follows. When the traffic is policed by a leaky bucket regulator, the token bucket size is equal to σ and the token arrival rate is equal to ρ. Thus, the traffic is bounded by an average rate and a maximum burst size. Such traffic is called regulated traffic and is denoted as $A \sim (\sigma, \rho)$. [11]

The cell injection mechanism is basically the addition of two traffic streams, each regulated as discussed above. This operation and the resulting traffic characteristics are illustrated in Figure 3.3.

$$A_1 + A_2 = \sigma_1 + \sigma_2 + (\rho_1 + \rho_2)\tau$$
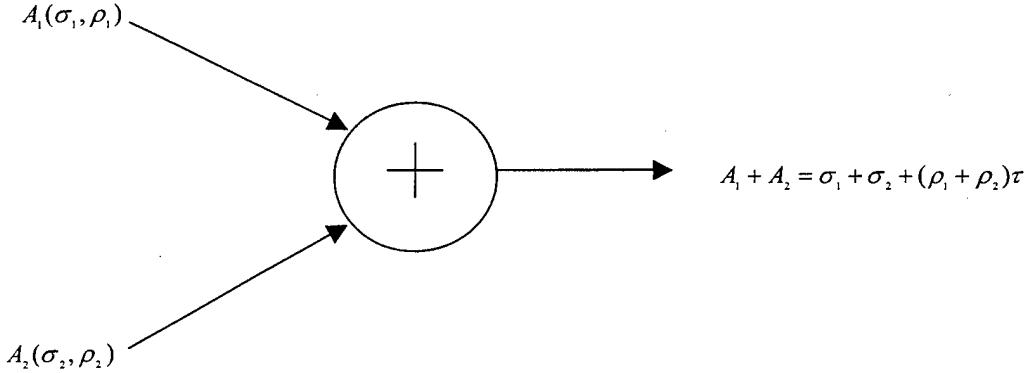
Figure 3.3 Addition of Two Traffic Streams [9].

The parameters σ and ρ corresponds to the MBS and SCR traffic parameters respectively. Considering a VBR connection policed by a GCRA algorithm, the aggregate stream must satisfy the following condition.

$$\sigma_1 + \sigma_2 + (\rho_1 + \rho_2)\tau \le \sigma + \rho\tau . \tag{3.3}$$

After further simplifying the Equation 3.3

$$\sigma_1 + \sigma_2 \le \sigma \text{ and } \rho_1 + \rho_2 \le \rho , \tag{3.4}$$

where σ and ρ are MBS and SCR for the virtual channel, respectively.

B.   STATISTICAL PROPERTIES OF ATM TRAFFIC

A discrete time random process representing ATM traffic can be described by its steady state, second and higher order statistics. Second order statistics are represented by the index of dispersion, autocorrelation function and power spectrum. Conventional queuing theory uses steady state statistics to model the queue response to an arrival process. In these models second and higher order statistics are generally ignored. However, second order statistics of the traffic can be determined in either time domain by autocorrelation function or in frequency domain by power spectral density function, and can provide additional insight.

Li et al. developed a new concept for spectral representation of arrival process in queuing analysis. Their studies [2]-[3], [12]-[13] have shown that the input power spectrum has an important effect on queue performance. From both analytical and empirical results, it

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was proven that the low frequency band power, which is a direct measure of traffic burstiness, has the dominant impact on queuing performance.

ATM traffic is modeled by Markov chains in order to capture the correlation properties. A two-state MMPP is a commonly used, basic model for traffic characterization of voice, video and data file transfer sources. Its autocorrelation function has a simple form that addresses the correlative and bursty nature of the source.

The model given in Figure 3.4 is considered the basic model for the cell injection. An on/off type user source of state-0 is masked with a cell-injecting source active in state-1. The goal in providing the model is to study the queue response to different inputs and to characterize the effects of cell injection on the second order statistics of the ATM traffic stream. The results drawn from the model simulations for different cases will be compared with the real network implementation results. Hence, the model will provide basis for understanding the real network implementation results.

This model is characterized by (P,γ) where p is a diagonalizable state transition matrix, and γ is the arrival rate vector representing the arrival rate at each state and denoted as $\gamma = [\gamma_0, \gamma_1, \gamma_2, ..., \gamma_{N-1}]$. The steady state solution of p is denoted by $\pi = [\pi_0, \pi_1, \pi_2, ..., \pi_{N-1}]$. The model's autocorrelation function has the following form [3]. (The derivation of the Equation 3.5 is provided in Appendix A.)

$$R(k) = \left(\bar{\gamma}\right)^2 + \psi_1 \lambda_1^k \tag{3.5}$$

Here $\psi_1 = \overline{\gamma^2} - (\bar{\gamma})^2$. The smaller eigenvalue of the transition matrix is denoted by $\lambda_1 = 1 - \alpha - \beta$ and the mean arrival rate is denoted by $\bar{\gamma} = \pi \gamma^T$. Taking the Fourier transform of autocorrelation function, the corresponding power spectral density function can be stated as

$$P(\omega) = 2\pi\delta(\omega)(\bar{\gamma})^2 + \frac{\psi_1(1 - \lambda_1)^2}{1 - 2\lambda_1 \cos(\omega T) + \lambda_1^2} \tag{3.6}$$

with $|\lambda_1| < 1$ and $P(\omega) = P(-\omega)$.

From the equations one can see that both the autocorrelation and power spectrum are characterized by the eigenvalues and mean arrival rate. The autocorrelation function consists

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of a geometric and a DC component. The DC component corresponds to an impulse function in the power spectral density.
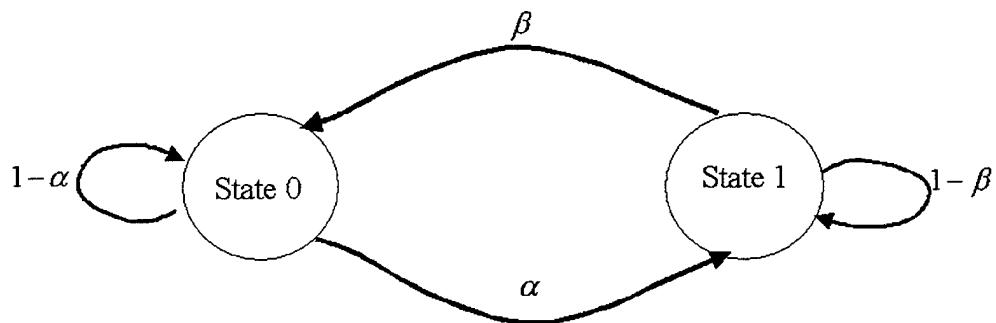

Figure 3.4 Two-State Cell Injection MMPP Model.

This model represents the most generic case because the input rate is assumed constant in each state. At a macro level this assumption is correct. When traffic is analyzed over long time durations, one can see that the average rate, SCR, dominates the traffic rate. However in reality the source will transmit at varying rates at micro levels, so the number of states will be more than two. The primary reason why an N-state (N can be 100, 200 etc.) MMPP model is not used is that the N-state transition matrix and corresponding input rates at each state are needed to be defined, a complex undertaking. As will be discussed, the two-state MMPP model still gives some valuable results to draw conclusions from regarding the cell injection mechanism.

Both the effects of varying eigenvalues and input rates on the statistical properties of the model and corresponding queuing response were studied using Matlab™ simulations. The state transition probabilities were assumed to be α =0.5 and β =0.02. Since the mean arrival rate appears as a constant term in the autocorrelation function, the magnitude of the autocorrelation function increases with an increase in the arrival rate. For increasing input rates at cell injecting state, the autocorrelation function exhibits a slow decaying trend, which is an indication of strong correlation of the arrival process over long time durations as illustrated in Figure 3.5. Hence, it can be concluded that the on-off nature of the source is removed by cell injection.

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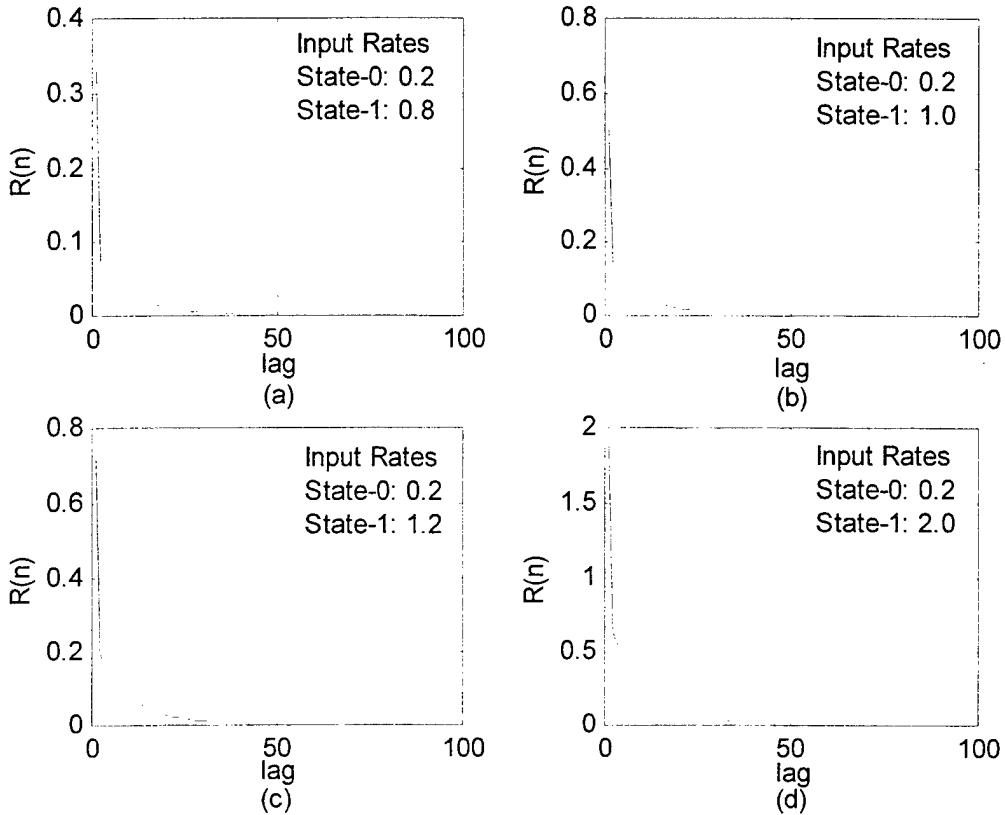
Figure 3.5 Autocorrelation Function of MMPP Model.

The power spectral density of the arrival process for different cell injection rates is given in Figure 3.6. Increasing average load, defined as $\rho = \overline{\gamma}/\mu$, gives rise to the DC power, which is the major factor in queue length distribution. In Figure 3.7 (b), queue response to increasing load with a fixed eigenvalue is illustrated. From the figure, the relationship between average load, DC power and the queue length can easily be verified.

Also the queue response to different eigenvalues is given in the Figure 3.7 (a). From the Equation 3.5, it can be concluded that as the smaller eigenvalue λ_1 approaches to one, the geometric term in the autocorrelation function approaches a constant term. Additionally, as the eigen value approaches one, which is the case for no transition or rare transition between states, the queue length increases drastically. Summarizing the simulation results, it can be seen that the queue response is determined by the mean and autocorrelation of the arrival process.
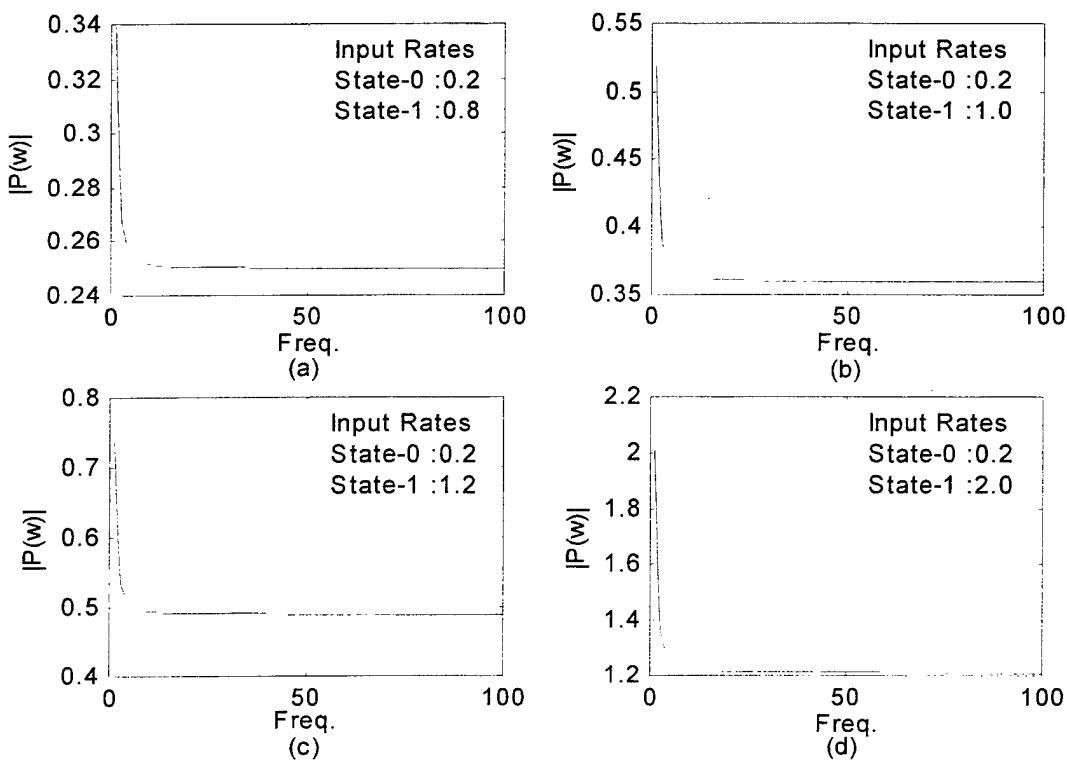
Figure 3.6 Power Spectral Densities of the Two-State MMPP.
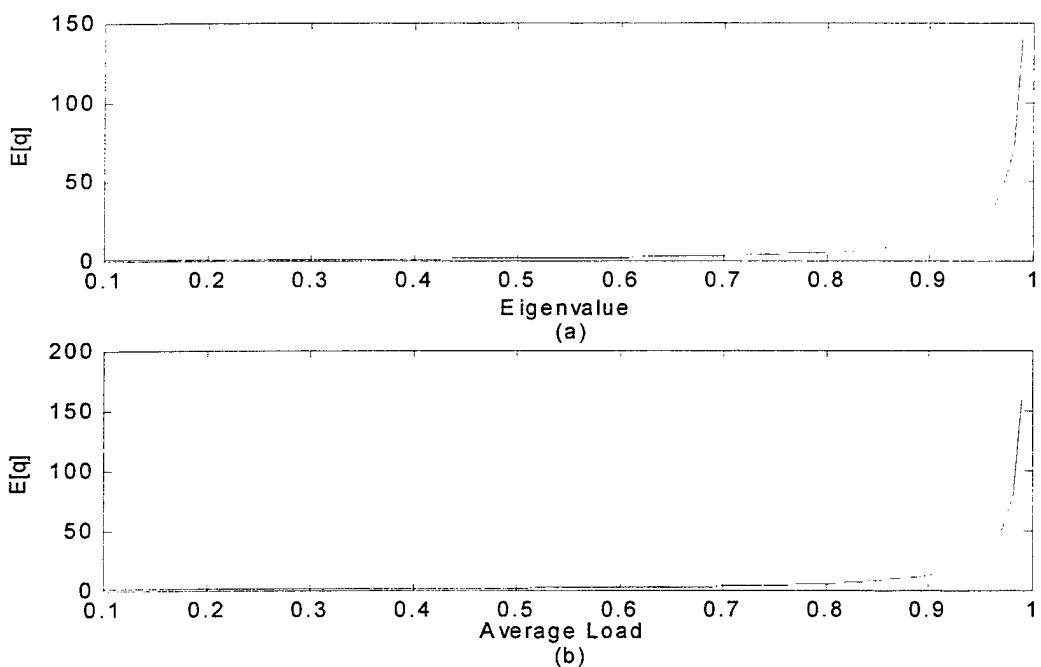
Figure 3.7 Queue Responses to Increasing Loads and Eigenvalues.

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In [13] and [14], a measurement window based on decomposing the traffic into three regions, low, mid and high frequency traffic, is proposed. The reason for diving the traffic into regions is ([14]) to localize traffic characteristics using quantitative statistic measures at each region and to define a timescale range of the arrival process that can affect the queue response [13]. The definition of each region both in time and frequency domain is given in Table 3.1.

Region	Time Domain	Frequency Domain	
Low	$s \geq 200 d_{max}$	$\|w\| \leq \|w_L\|$ where $\|w_L\|$ $0 < w_L \leq \dfrac{0.01\pi}{d_{max}}$	$d_{max} = \dfrac{K}{\mu}$ K=Buffer capacity μ =Service rate
Mid	$\left(d_{max}, 200 d_{max}\right)$	$\|w_L\| \leq w \leq w_H$	
High	$s \leq d_{max}$	$\|w_H\| \geq \dfrac{2\pi}{d_{max}}$	

Table 3.1 Traffic Regions.

In the definitions, the regional boundaries are based on maximum queuing delay, which is denoted by d_{max}. It is well known from queuing theory that buffering can alter traffic dynamics to some extent, known as "traffic smoothing". From the Table 3.1, it can be seen that high frequency variations define a region in which buffering can easily absorb the variations in the arrival process. Whereas low frequency region, where values tend to be considerably greater than the maximum allowable queuing delay, represents the timescale in which buffering cannot alter the traffic characteristics. This region is known as the buffer non-effective region [13]. The mean arrival rate, the DC component in the power spectral domain, falls into the buffer non-effective region and, therefore, its characteristics remain unaltered after the queuing process.

Consider an example traffic region calculation in the frequency domain for an OC-3 link (155 Mbps) and a buffer size of K = 500 cells. The maximum allowable delay is going to be $d_{max} = 1.37\,ms$, and the corresponding traffic regions are going to be: $0 \leq \omega_L \leq 3.66 Hz$, $3.66 \leq \omega_M \leq 730 Hz$ and $\omega_H \geq 730 Hz$.

IV. AX/4000 ATM TEST SYSTEM AND TEST MODEL

A. AX/4000 ATM TEST SYSTEM

The ADTECH™ AX/4000 is a hardware-based test system designed for measuring the performance of ATM networks in real time based on user-defined scenarios. The performance tests include physical layer testing, ATM transmission QoS testing, network load testing and live ATM traffic monitoring. It is packaged in a rack-mounted chassis. The main components are the chassis with a General Purpose Interface Bus (GPIB), controller module, an external controller, generator/analyzer modules and physical port interfaces (e.g., OC-3c/STM-1 Single Mode, DS3, OC-12c/STM-4c). The port interfaces provide a physical interface between the ATM physical layer and the AX/4000 modules. Windows®-based controller software provides different setup and test control parameters to the user.

The user interface makes use of block diagrams to show the flow of the signal path being tested. Each block is accessible for parameter changes. The system configuration and measurement results can be saved on disk for further analysis. The captured data can also be exported to the other processing software environments, such as Excel or Matlab. The system components and some of the basic functions will be discussed in the next section.

1. Generator Module

The ATM Generator module creates user defined cell streams that simulate real traffic patterns. The generator module occupies one chassis slot and provides one port and up to eight programmable traffic sources.

Of the eight sources, seven are foreground traffic sources while one is a background source as shown in Figure 4.1. When the background source is not used, only unassigned cells will be transmitted while the foreground sources are idle. Otherwise the background source will transmit user-defined cells when the sources are silent.

Each source and the aggregate stream have a traffic shaper that implements the ATM Forum's Generic Cell Rate Algorithm (GCRA). Traffic shaping allows the user to limit the minimum average cell spacing and burstiness of the traffic stream to prevent cell clumping. The shaped, or smoothed, cell stream is expected to conform to a traffic contract

based on PCR, SCR, CDVT and MBS. Nonconforming cells will either be tagged or dropped depending upon user selection.
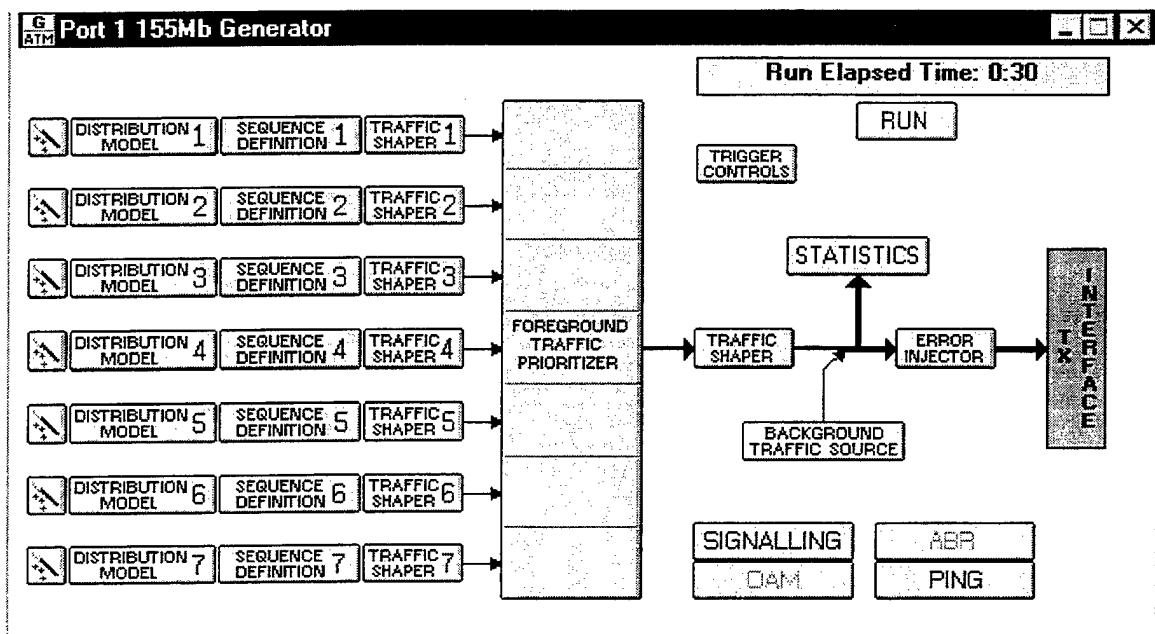
Figure 4.1 Generator Dialog Box.

The foreground traffic prioritizer is used to simulate the effects of different ATM classes of service on the traffic. The foreground sources may have one of the four priority modes simulating one, two, three, or seven classes of service. The background source is always assigned the lowest priority.

The AX/4000 provides a wide variety of statistical cell distribution models for its foreground sources to simulate different traffic patterns such as Constant Bit Rate (CBR), Variable Bit Rate (VBR) and Unspecified Bit Rate (UBR). Each foreground source can use any of the 12 models ranging from manually trigged cells to a sequence controlled Markov Modulated Poisson Process (MMPP) that can be periodic or bursty. The user can configure the cell header field values and select the payload type available by the system such as AAL0, AAL1, AAL5, OAM and QoS test cells.

2.   Analyzer Module

The analyzer module monitors the traffic stream, provides QoS measurements and statistics, and displays the raw data being carried. The measurements include aggregate cell count, uncorrected header error count, and corrected header count. The Analyzer dialog box is shown in Figure 4.2.
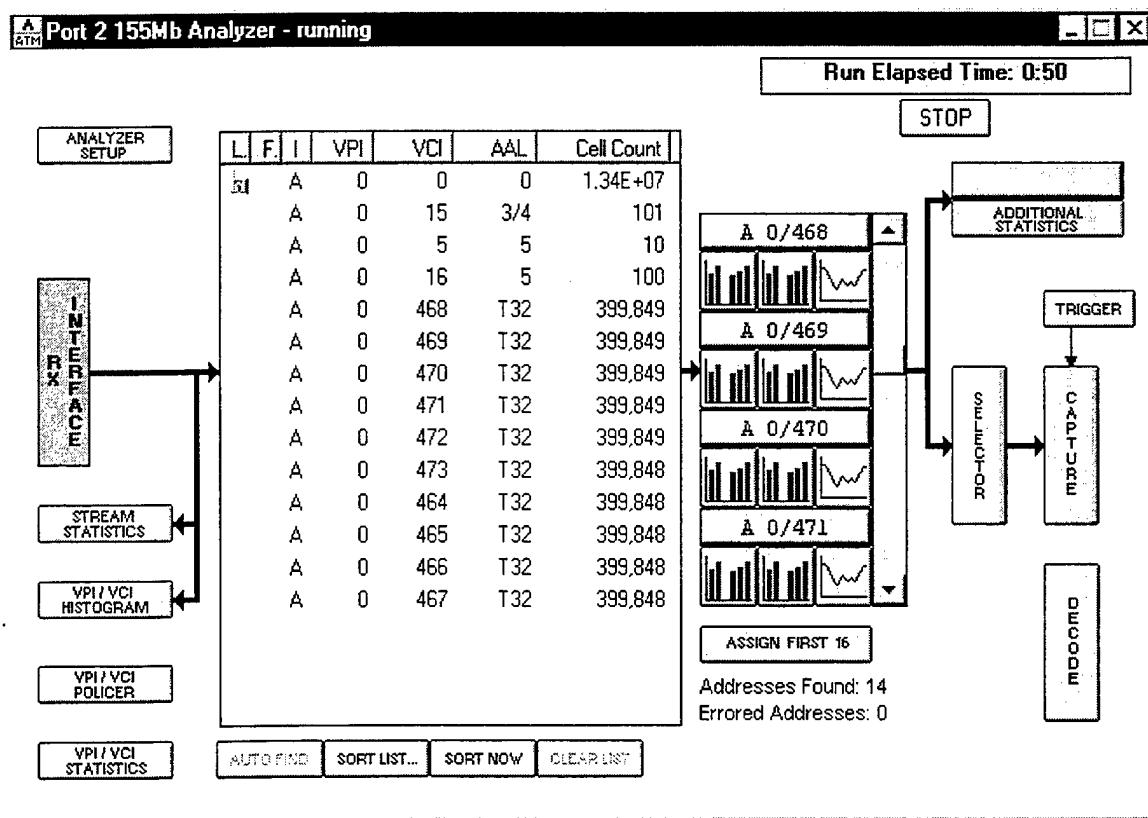
Figure 4.2 Analyzer Dialog Box.

In addition to these composite cell stream measurements, the analyzer module provides 16 cell filters, which can be configured to divide the composite traffic stream into separate substreams for detailed analysis.

The cell capture function provides full rate cell or header only capture options for more detailed analysis. The captured cells can be from any combination of the 16 substreams or non-captured cell streams such as unassigned cells. Captured cells can be reassembled and saved to a file for retransmission in any of the foreground or background

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sequences. Cell capture can be triggered both manually and by an event such as matching a specific error mask, exceeding peak cell rate thresholds or non-compliant cell occurrences.

In addition to numerical data, the analyzer can also generate histograms for each substream based on Cell Transfer Delay, Cell Inter-arrival Delay, Cell Loss Count, Congestion ratio, and many other QoS measurements.

For each substream, traffic policing can be applied to the incoming traffic stream to test traffic contract compliance.

B. TEST MODEL

1. System Configuration

A two-node ATM network, currently installed at the Naval Postgraduate School's Advanced Networking Laboratory, was used to implement cell injection and performance measurements. Figure 4.3 illustrates the physical layout of the measurement model that includes an OC-12 (622 Mbps) link between two nodes and OC-3 (155 Mbps) links for AX/4000 local connections.

Various hardware and software aspects of the switch such as VPI/VCI connections and their traffic contract definitions, SNMP network management, and QoS parameters are configured via switch control software (SCS).
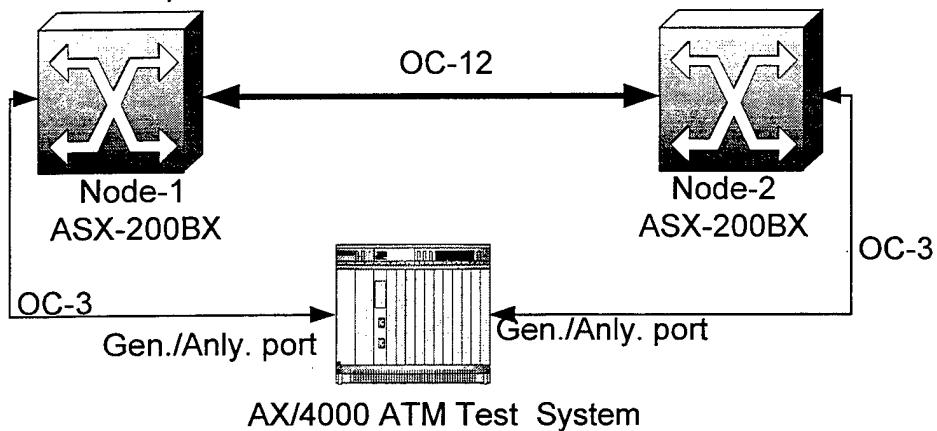

Figure 4.3 Physical Layout.

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2.   Test Set Up

A unidirectional permanent virtual channel between two nodes was configured to implement cell injection. The AX/4000's generator and analyzer modules simulate the sending and receiving end-stations. UPC tables were configured at both switches to implement traffic policing on a VBR connection. In order to emphasize the fact that in real applications, traffic traversing through multiple ATM nodes may experience different traffic policing functions, UPC entries were defined differently at both nodes. The UPC parameters at both nodes are provided in Table 4.1. The UPC definition implies a dual leaky bucket policing on the traffic flow in which both CLP=0 and 1 type cells will be checked for compliance. The UPC action on non-conforming cells was set to cell dropping.

Traffic Type	Node-1 (Generator)	Node-2 (Analyzer)
VBR01	PCR01=4000 cps SCR01=2700 cps MBS01=600 cps CDVT=2200 μs	PCR01=3500 cps SCR01=2400 cps MBS01=400 cps CDVT=2000 μs

Table 4.1 UPC Table Entries for Permanent Channel.

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V. ANALYSIS OF CELL INJECTION OVER A VBR TRAFFIC STREAM

In Chapter IV, a permanent VBR connection between the AX/4000 ATM test system's generator and analyzer ports through two ATM switches was established. As described in Chapter III, there are several possible implementation scenarios that we can consider to re-characterize traffic flow. In this chapter, one such example is analyzed. The methodology and the approach taken in the example can be applied to other traffic combinations as well.

A.   VBR-to-VBR TRANSFORMATION ANALYSIS SETUP

In this experiment, cell injection was implemented over a VBR traffic stream to transform it into another VBR traffic stream having a new average rate (SCR) and variance (MBS). The original source was configured to produce a bursty video traffic. The channel allocation is listed in Chapter IV. The injection model is illustrated in Figure 5.1. The original source was modeled with an on-off type source transmitting randomly spaced bursts. At each burst, it generates a random number of cells and goes back to the idle state after transmission. Transitions from the idle state to the active state are also randomly spaced.

The cell-injecting source was modeled with the same type of source as that of the original source. The difference between the two of them was that the gap between idle and active periods was set to a smaller value for the injecting source compared to the original source. The burst state cell generation was again random.

The average burst size controls the variance of the aggregate cell rate. One of the goals in cell injection is to change the variance of the cell stream as well as its mean. Hence, the injecting source average burst was defined at a rate higher than the source rate.

As presented in Chapter IV, the traffic prioritizer resolves the cell contention from multiple sources. In this implementation, seven levels of decreasing priority, starting from first source to seventh source were used. The highest priority source, which is source one, represents the original user and the second highest source represents the cell-injecting source. The scheduling algorithm for this priority scheme allows a lower priority service

source only to send whenever a higher priority source is idle. Thus, the scheduling algorithm's action supports the goal of cell injection by regulating the transition between original sources and the injecting source during on-off times.

The QoS measurements such as cell loss ratio and cell transfer delay were done by using the AX/4000's built in test cells. These cells use time stamp and sequence number information in the payload and are separately defined in the original source cell sequence aside from other payload types.

Cruz bounds [9] were applied in order to determine the upper bounds on burst size and long-term average rate for each source to prevent traffic contract violations. Using the original source parameters and virtual channel UPC parameters one can define the cell-injecting source parameters as follows:

- $\sigma_2 \leq \sigma - \sigma_1$ where σ_1 is the original source MBS and σ the channel MBS.
- $\rho_2 \leq \rho - \rho_1$ where ρ_1 is the original source SCR and ρ is the channel SCR.
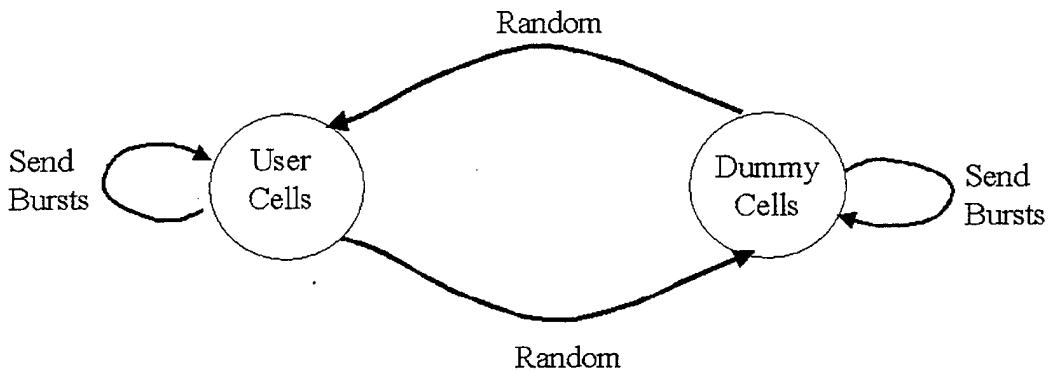
Figure 5.1 VBR Bursty Source Cell Injection Model.

Recall from Chapter IV that the UPC definition for each ATM node is set to be different in order to emphasize the fact that the traffic may experience different UPC actions. Hence, the upper bounds in this case would be the node whose UPC parameters are the smallest among nodes throughout the connection. After applying the bounds, the original source and cell injecting source traffic parameters are found as given in Table5.1.

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Traffic Parameter	Permanent Virtual Channel	Original Source	Cell Injecting Source
Average Cell Rate	2400 cps (*)	800 cps	1600
Average Burst Size	400 cps (**)	100 cps	300

(*) SCR (**) MBS

Table 5.1 Source Traffic Parameters.

The original source has an average-to-peak ratio of 8/35. A long off and a short on period was considered to be the best case burst gap for demonstrating the cell injection as there would be enough unassigned cell slots to be of use. For the original source, the average gap, or silence duration was designed to be 0.273 sec and active duration, was 0.273 msec. On the other hand, the cell-injecting source was designed to have an active duration of 0.819 msec and silence duration of 0.136 msec. For each source the burst size was set to random in order to simulate cell rate fluctuations.

B.   ANALYSIS OF RESULTS

Figure 5.2 (a) illustrates the time series plot of the original traffic. The source characteristics such as burstiness and traffic volume, quantified by the mean rate, can easily be observed from the captured traffic.

After the injection the traffic volume increased and the utilization was shifted up to a predetermined value as shown in Figure 5.3 (a). Some observations can be made from these results as follows. First, the on-off nature of the source is hidden. Second, the volume of the traffic per unit time is shifted nearly up to sustainable rate. To an outside observer, the original source characteristics such as utilization, mean and variance are effectively hidden.

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Cell injection has certain effects on the QoS parameters of the original connection. Cell Transfer Delay (CTD), Cell Loss Ratio (CLR) and Cell inter-arrival time measurements pertaining to before and after cell injection scenarios are provided in Appendix B. Along with an increase in the average load, the mean cell inter-arrival time was decreased. As shown in Appendix-B Figure B1, the inter-arrival time distributions fit into an exponential distribution for both scenarios. The mean inter-arrival time was almost halved from 1.13201 msec. to 0.50567 msec. A decreased cell inter-arrival has the following effect on the queuing system. The policing algorithm, namely GCRA, requires a cell to arrive after or on time defined by a Theoretical Arrival Time (TAT). As cell inter-arrival time decreases, some of the cells arrive at the queue early and are considered non-conforming cells. Since the queue action was set to "cell dropping," the connection's cell loss ratio at different time instants was increased as shown in Figure B2. The histogram of CLR and CLR values zoomed around 0.004 are also given in Figure B2.

Figure B3 illustrates average CTD for both original and cell injected traffic streams on the same figure. The interval around 170-210 sec. represents CTD for the original stream in which the delay was zero. The reason for zero delay is that two switches interconnected locally and therefore no transmission delay exists. The active duration of the source was short enough that queuing did not yield any delay. After the injection cell transfer delay increased due to additional queuing and processing time in the switch. For delay sensitive applications such as rt-VBR, the degree of injection should be considered carefully from the quality degradation point of view and therefore delay should place another constraint on the injecting source traffic parameters.

The second order statistics of both the cell-injected and original stream will be discussed next. The autocorrelation estimate of the original stream is shown in Figure 5.2 (b). The asymptotic slow decaying nature of the autocorrelation function implies strong correlation in the arrival process, which is an indication of long-range dependency in the arrival process. It can be seen from Figure 5.3 (b); that the correlative properties of the traffic are highly emphasized after the cell injection. The magnitude at lag zero is increased. Like the original source, the aggregate traffic exhibits strong correlation over long durations.

Recall from Chapter III that the frequency spectrum of the ATM cell stream is divided into three regions: low, mid and high frequency. Taking the buffer size as 256 cps

and $\mu^{-1} = 2.735\,\mu\sec$ the maximum allowable delay will be, $d_{max} = 0.7\,ms$. The corresponding regions are then:

- $\omega_L = \dfrac{1}{200 d_{max}} = 7.14\,\text{Hz}.$

- $\omega_H = \dfrac{1}{d_{max}} = 1428\ \text{Hz}.$

- $7.14\,\text{Hz} \leq \omega_H \leq 1428\,\text{Hz}.$

Power spectral density estimates of both the original and cell-injected traffic are given Figure 5.4 in absolute and in Figure 5.5 in dB scale. Recall from the analytical results, it was shown that the DC power, or mean arrival rate, dominates the queue length. From both the original and cell injected traffic spectral densities, it can be seen that the DC component is the dominant component in the frequency spectrum. As cells are injected, more power in the mid frequency region shifted towards to the low frequency region increasing DC power. When more power is shifted towards the low frequency region, buffering becomes less effective to smooth out the traffic dynamics. The result provides another explanation for cell loss ratio increase after the cell injection shown in Figure B2 in Appendix-B.
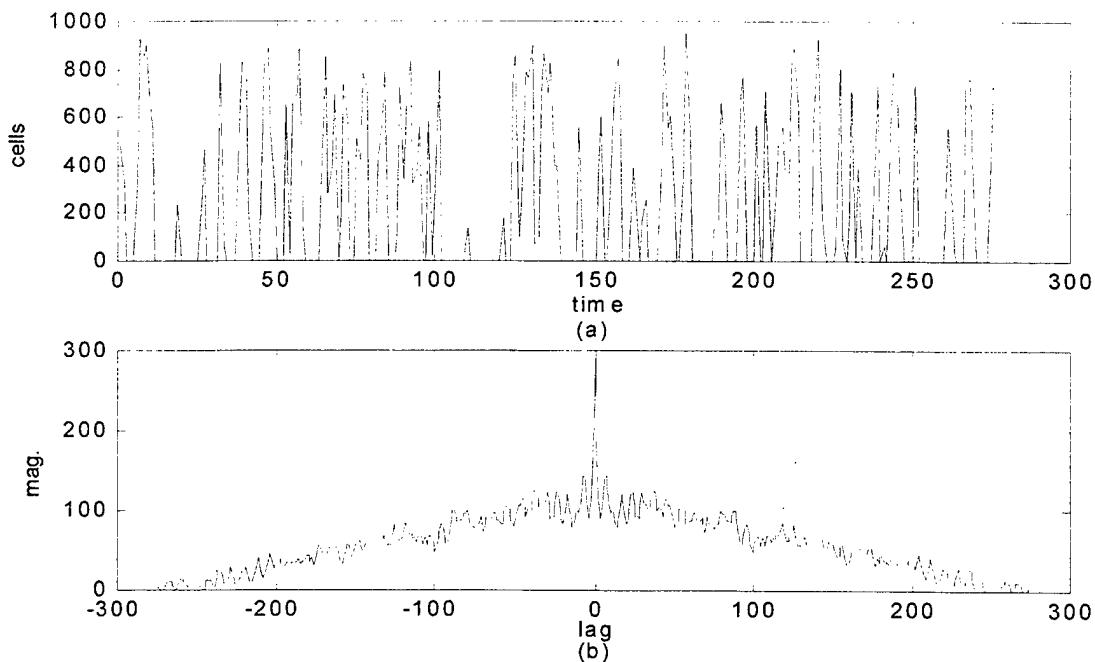

Figure 5.2 Original Stream and its Autocorrelation Function.

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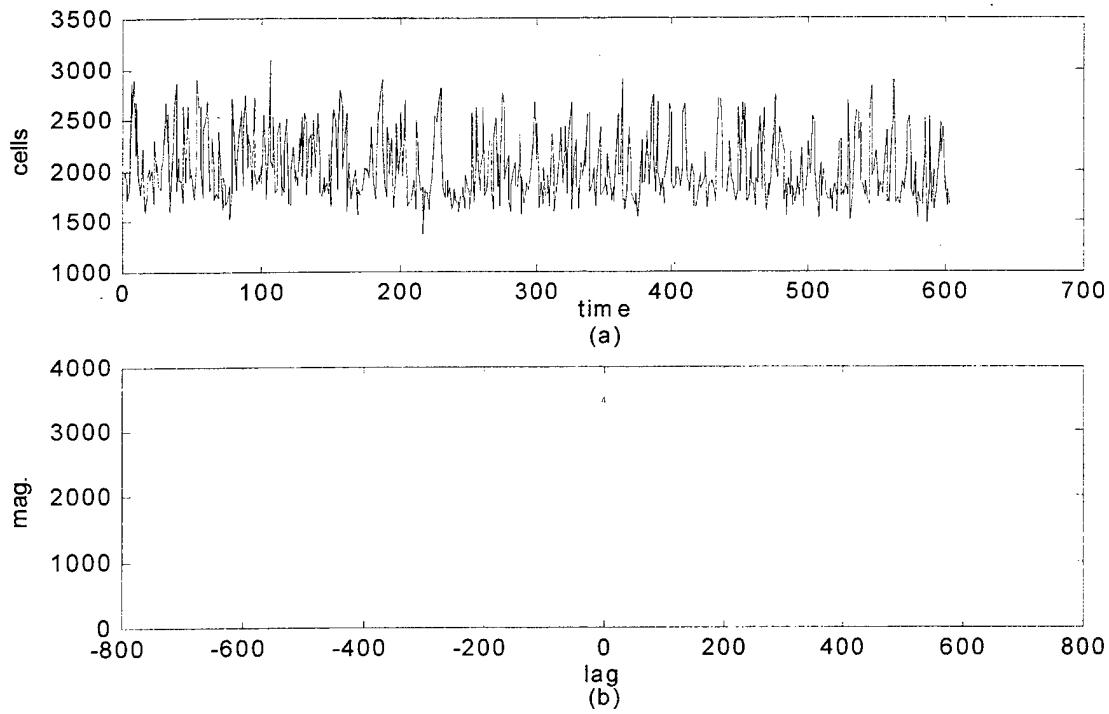
Figure 5.3 Cell Injected Stream and its Autocorrelation Function.
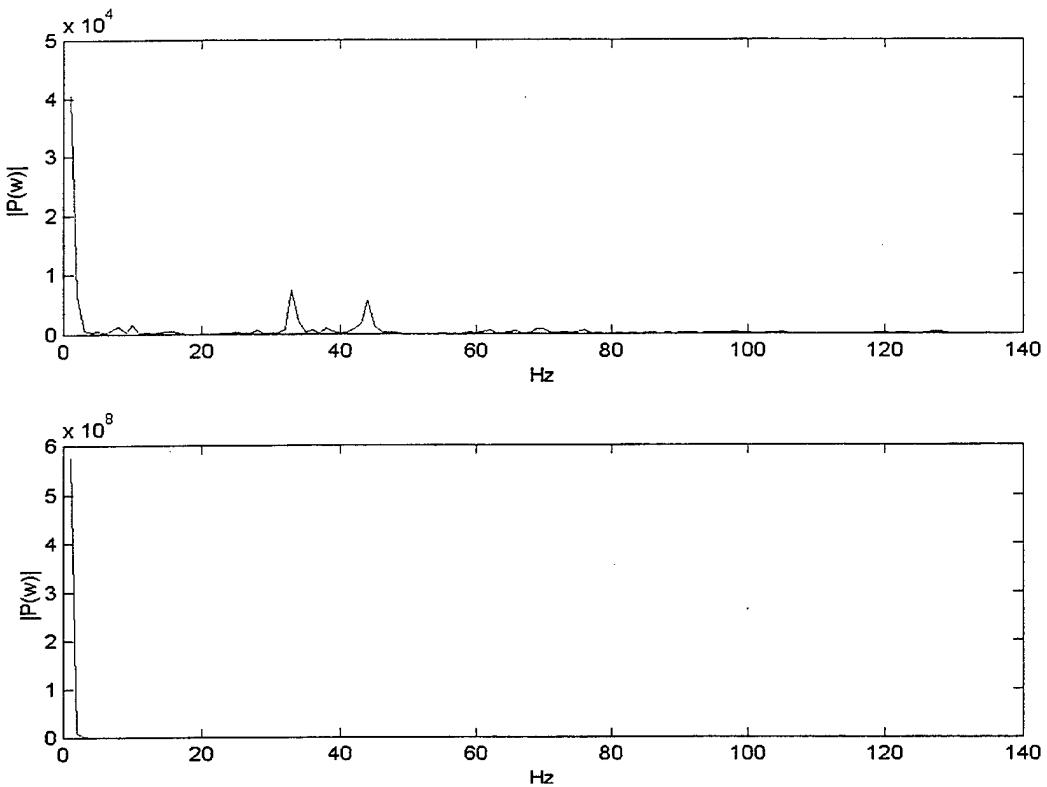
Figure 5.4 Power Spectrum Estimates. (a) Original Traffic (b) Cell Injected Traffic

44
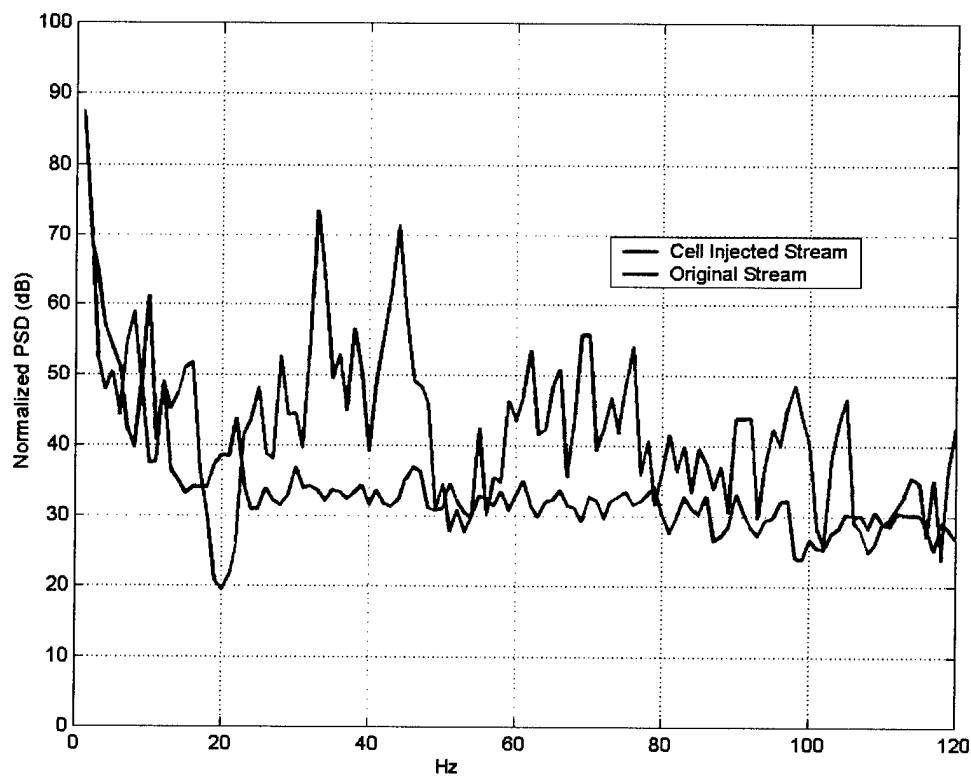
Figure 5.5 Power Spectrum Estimates on the Same Figure.

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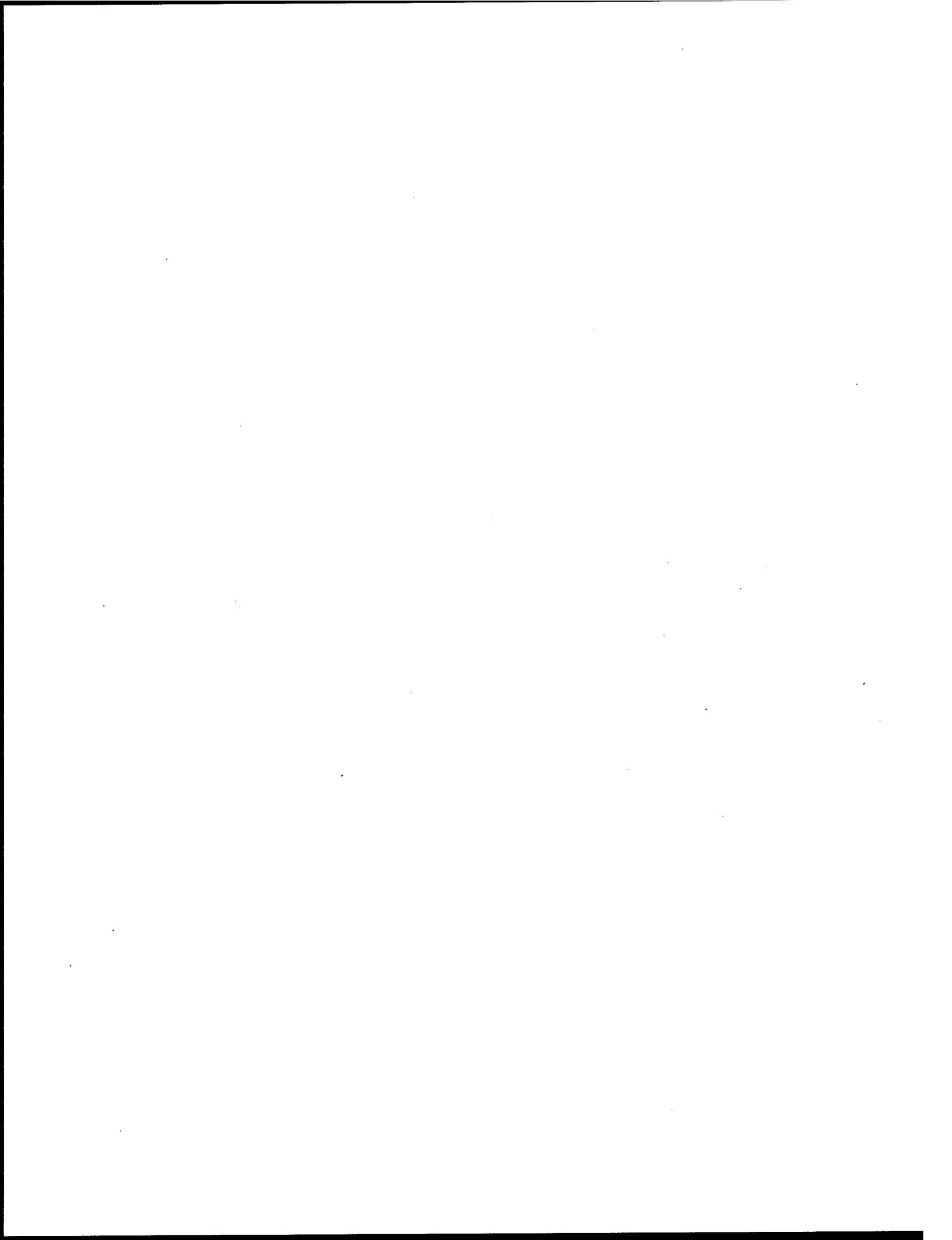
VI. CONCLUSION

A.   SUMMARY OF WORK

This thesis investigated a method for virtual connection utilization masking in ATM networks. The problem was defined as the summation of two random processes each of which has different statistical characteristics. In order to provide background for understanding the network implementation results, a theoretical analysis of cell injection was studied with a two-state MMPP model. Specifically, in light of the theories developed by Li et al., queue response to varying arrival rates, the autocorrelation and power spectral densities of the cell injected traffic were examined. The goal was to define the effects of cell injection on the spectra of arrival process. An MMPP model was chosen because Markov chains have proven to be the best at capturing correlative properties of traffic streams. The simulation results showed that as the arrival rate increased, the autocorrelation function demonstrated a strong correlation over long time durations. As the utilization approached a flat level, the magnitude of the zero lag increased. The queue response to varying loads indicated that the queue length would be dominated by the average arrival rate, or by DC power in the frequency domain.

The cell injecting source traffic contract parameters were defined by using Cruz bounds. The results obtained from these bounds give the user enough flexibility to shape the aggregate traffic. As long as the traffic-contract limits are not exceeded, any variance and mean can be added to the original stream.

Among several possible implementations propesed in Chapter III, VBR traffic utilization masking was studied. The reason for implementing VBR traffic masking is that the bursty nature of VBR sources would best explain the idea of cell injection as they usually underutilize the allocated resources.

In the AX/4000 ATM test system, two source models were defined to represent original and cell injecting sources. A built-in scheduling algorithm regulated the transition between the two of them. From the captured traffic data, it was proven that the volume of the traffic increased to channel's average rate, and the injection effectively and flexibly masked the original traffic characteristics.

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By computing the autocorrelation and power spectral densities of the real cell-injected ATM traffic, the MMPP model results were validated. It was observed that cell injection caused mid and high frequency traffic power to be shifted towards the low frequency region. As cells are injected, the burstiness of the stream was removed and the mean arrival rate increased.

Finally, it was also observed that cell transfer delay and cell loss rate were increased. Therefore, for delay sensitive real time applications, cell transfer delay should be another constraint on the amount and timing of cell injection. Otherwise, as verified from the results, QoS degradation will occur. These results also comply with the simulation results as increasing DC power results in increasing cell loss ratio in a finite buffer system, such as an ATM node.

B.   FUTURE WORK

Some of the possible future studies are given below:

- The cell injection was implemented over a permanent virtual channel that does not require any signaling procedures for connection establishment. On the contrary, the switched virtual channels (SVCs) establish a virtual channel via signaling. The information elements (IE) in the signaling message include source and destination addresses as well as traffic contract parameters and conformance definition. Therefore, injecting cells into the user stream may not be enough to mask connection utilization. The signaling channel may also reveal valuable information about the connections. Hence, masking signaling channels must also be considered.

- Although it is dynamically allocated and exists only for the duration of the connection, the SVCs are also susceptible to traffic measurement attacks. Despite permanent channels, the SVC traffic contract is negotiated each time the source requests a connection. Therefore, the amount of injection should also be determined dynamically as opposed to the static definition used in PVCs. Further study would be planned on developing an adaptive cell injecting source model.

- The AX/4000 ATM test system's source distribution models were used in testing. These models provide statistical properties of existing service classes. Along

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with the statistical measurements, such as cell loss ratio and cell transfer delay, perceptive measurements would also be important in rt-VBR traffic. For instance, QoS measurements may indicate that the QoS parameters still maintain the agreed contract. But the actual video or voice quality may be perceptually unsatisfactory. Therefore, cell injection could be implemented on a real traffic stream, either voice or video, to examine both statistical and perceptual degradations. Since the primary goal in injecting cells is to mask but at the same time maintain the existing quality of the traffic, the results may be incorporated into the injecting source model definition.

- The injecting source model in AX/4000 ATM test system is based on two traffic parameters, average load and maximum burst size. Despite the fact that the source definition supports the essence of cell injection by providing an average load of traffic, the user has a loose control over the cell-injecting source at the micro level. More precise cell-injection schemes can be developed by using AX/4000 ATM test system's C functions. A follow on study would be planned on developing source C code and algorithms that will determine the amount and timing of cell injection accurately.

- During implementation, the propagation delay between ATM nodes was ignored. But as stated in Chapter V, delay should place another constraint on the amount of injection. Therefore, a communication channel simulator can be used to study the relationship between delay and cell injection especially for delay sensitive traffic.

- Recognizing and discarding injected cells at the receiving user end would be another research topic to dwell on.

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APPENDIX A. AUTOCORRELATION FUNCTION OF TWO-STATE MMPP

Consider a two-state Markov chain (MC) with transition matrix defined as $P = \begin{bmatrix} 1-\alpha & \alpha \\ \beta & 1-\beta \end{bmatrix}$

In general any diagonalizable matrix and its nth order power can be written as

$$A = S\Lambda S^{-1} \text{ and } A^n = S\Lambda^n S^{-1} \tag{A1}$$

S is the eigenvector and Λ is the diagonal eigenvalue matrix. Assuming p is diagonalizable, and using the spectral decomposition theorem, p can be rewritten as follows

$$P = \sum_k \lambda_k g_k h_k = \lambda_1 g_1 h_1 + \lambda_2 g_2 h_2 + \ldots \lambda_k g_k h_k \tag{A2}$$

where g_k and h_k are the right column vector and left row vector of the eigenvector matrix, with respect to eigenvalue λ_k and are defined as

$$g_k = \begin{bmatrix} g_{k0} \\ g_{k1} \\ . \\ . \\ . \\ g_{k(N-1)} \end{bmatrix} \quad \text{and} \quad h_k = \begin{bmatrix} h_{k0} & h_{k1} & \cdots & h_{k(N-1)} \end{bmatrix} .$$

Further define an input rate vector; $\gamma = [\gamma_0 \quad \gamma_1]$. In [3] the correlation function of the input is given by

$$R(n) = E\{\gamma(m)\gamma(m+n)\} = \sum_i \sum_j \gamma_i \gamma_j P^n \pi_i \tag{A3}$$

where π_i is the ith element of the steady state probability vector and $\gamma_i = \gamma(i)$. Using the Equations A1 and A2, the autocorrelation function can be rewritten as

$$R(n) = \sum_l \psi_l \lambda_l^n \tag{A4}$$

with $\psi_l = \sum_i \sum_j \gamma_i \gamma_j g_{li} h_{lj} \pi_i$.

Expanding the Equation A4 for two-state MC autocorrelation function $R(n)$;

$$R(n) = \psi_0 \lambda_0^n + \psi_1 \lambda_1^n \tag{A5}$$

Further simplification can be done since the eigenvalues are; $\lambda_0 = 1$ and $\lambda_1 < 1$

$$R(n) = \psi_0 + \psi_1 \lambda_1^n \qquad \text{(A6)}$$

Since one of the eigenvalues is less than one, in the limiting case when $n \to \infty$ given in [3] as

$$R(\infty) = \psi_0 \quad \text{and} \quad R(n) = E\{\gamma(m)\}E\{\gamma(m+n)\} = (\bar{\gamma})^2. \quad \text{Hence,} \quad \psi_0 = (\bar{\gamma})^2 \qquad \text{(A7)}$$

Parseval's theorem states that the average input power in the discrete time domain and the frequency domain must be equal. In other words;

$$\overline{\gamma^2} = R(0) = \frac{1}{2\pi} \int_{-\pi}^{\pi} P(\omega)d\omega \quad . \quad \text{Substituting } R(0) \text{ in Equation A4, the average power can be}$$

written as

$$\overline{\gamma^2} = \sum_{l=0}^{N-1} \psi_l \qquad \text{(A8)}$$

where N is the number of states and ψ_l is given in the Equation A4. The average input power for two-state MC can therefore be written as

$$\overline{\gamma^2} = \psi_0 + \psi_1 \qquad \text{(A9)}$$

Substituting the result for ψ_0 from the Equation A7,

$$\psi_1 = \overline{\gamma^2} - (\bar{\gamma})^2 \qquad \text{(A10)}$$

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# APPENDIX B. CELL INTERARRIVAL TIME, CELL LOSS RATIO AND CELL TRANSFER DELAY CAPTURES


(a)

(b)
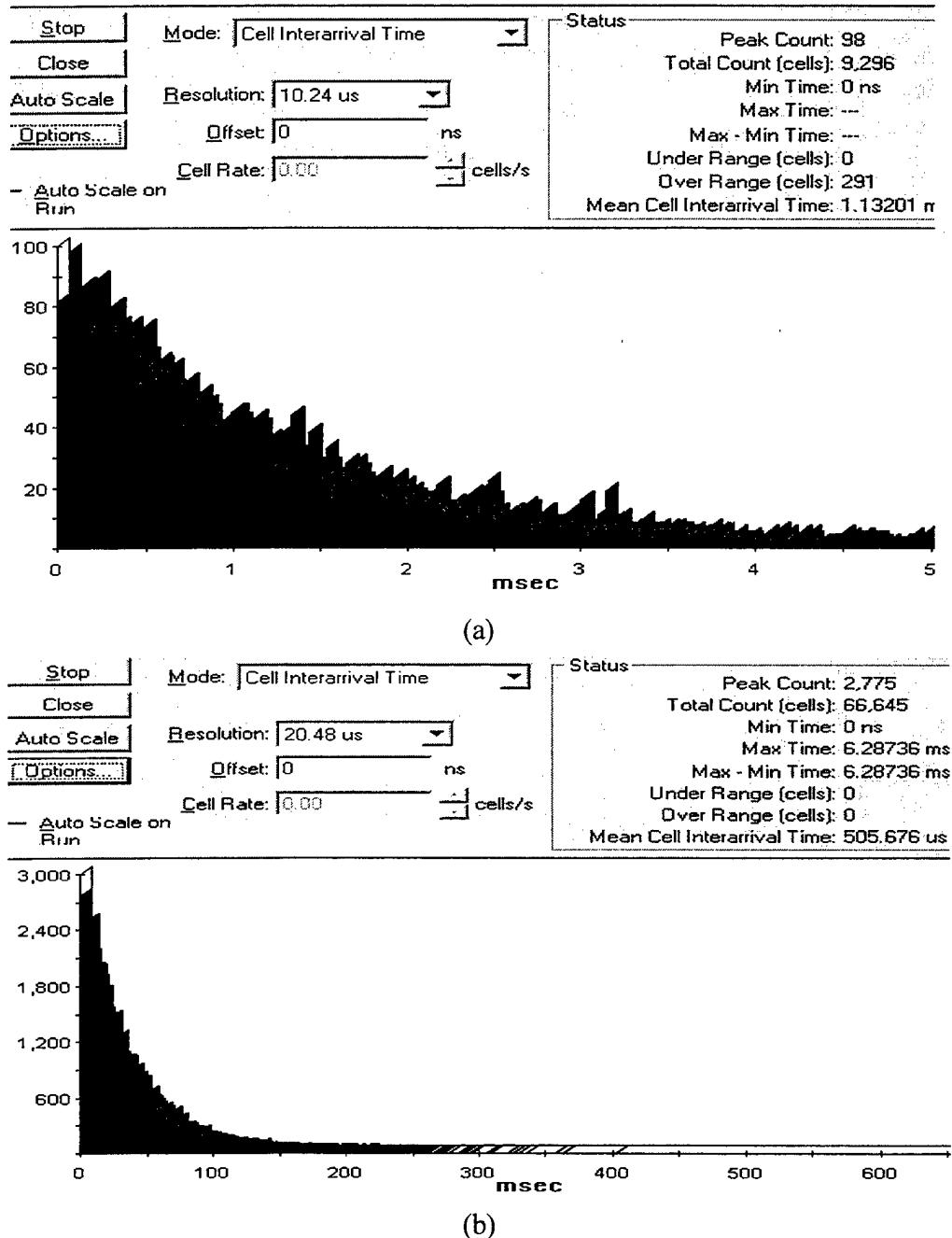
Figure B1 Cell Inter-arrival time. (a) Before   (b) After the Cell Injection.
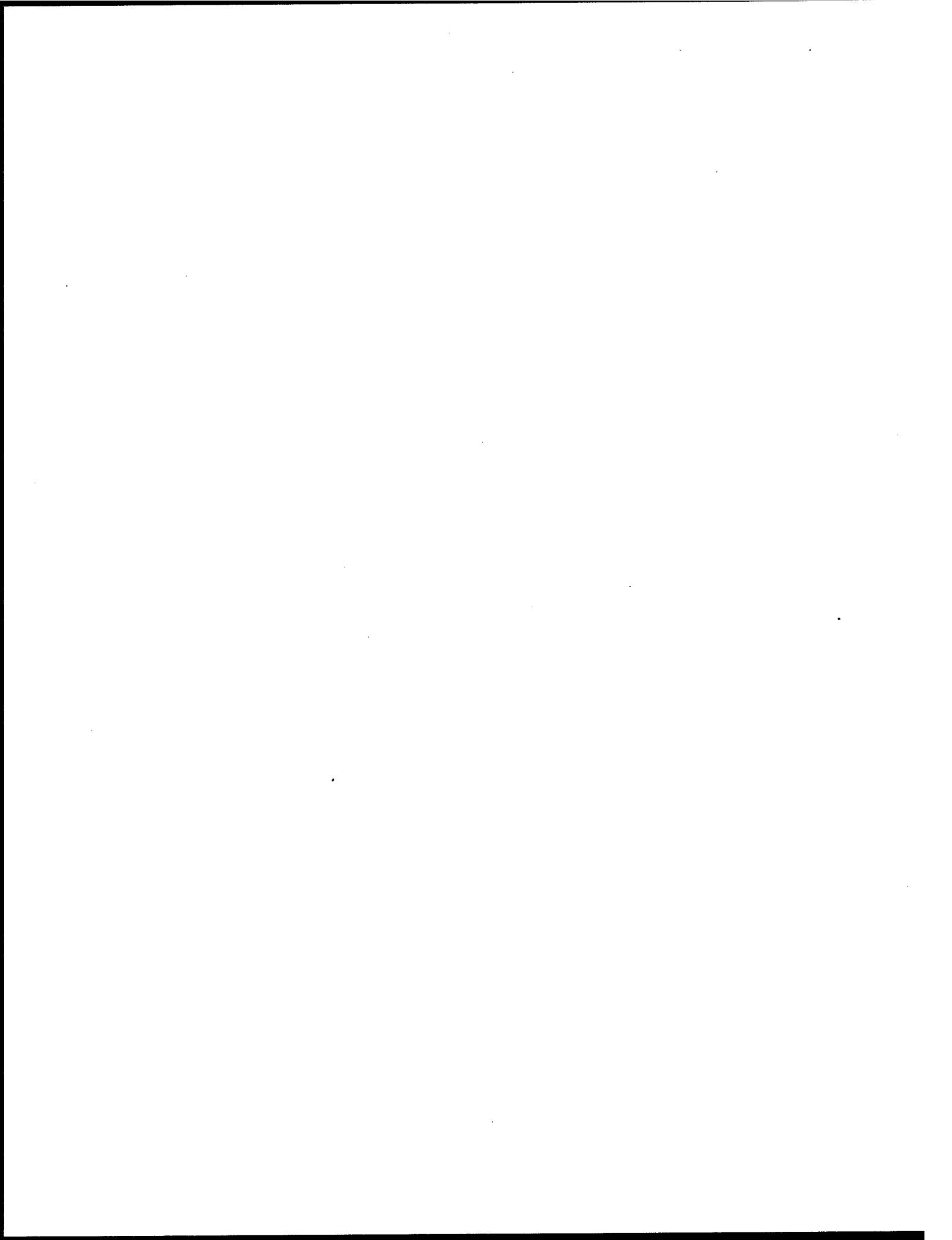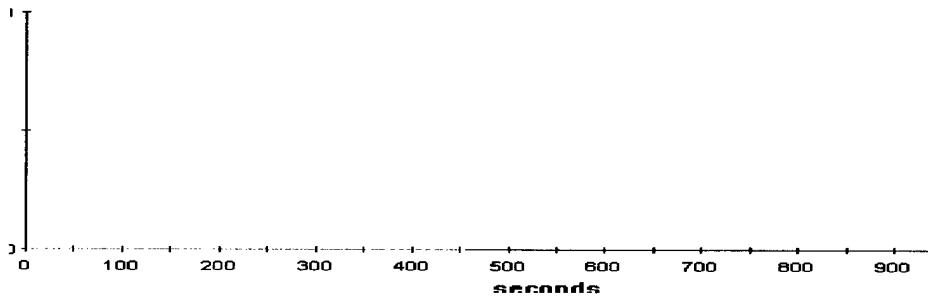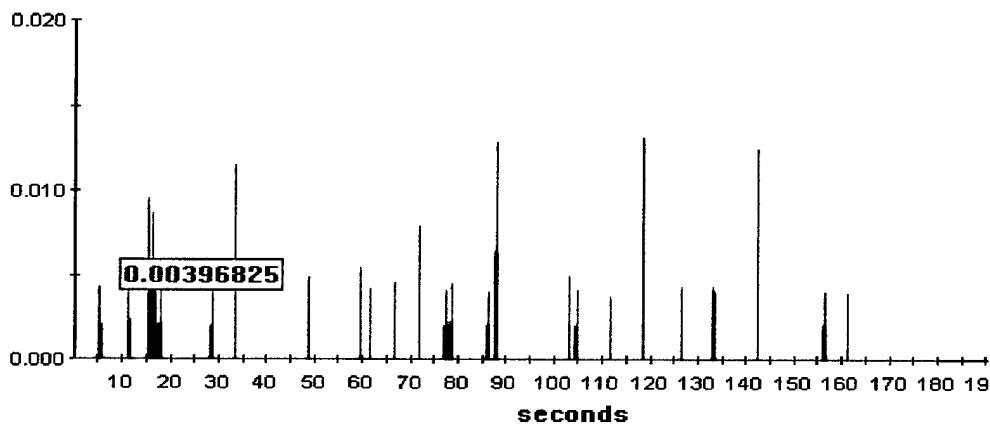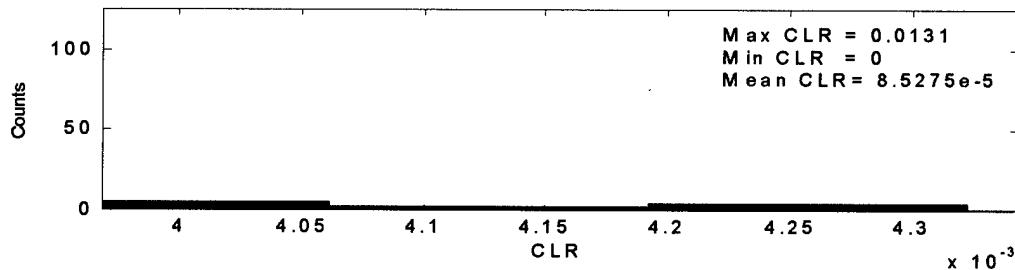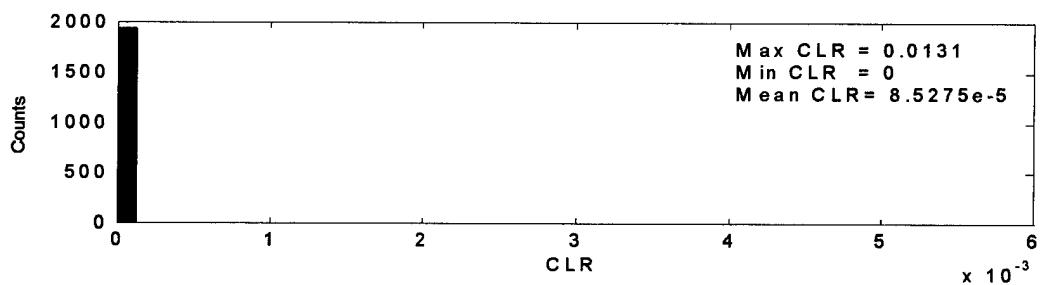
Figure B2 Cell Loss Ratio. (a) Original Stream (b) After the Injection (c) CLR Histogram
and Zoomed CLR Values around 0.004
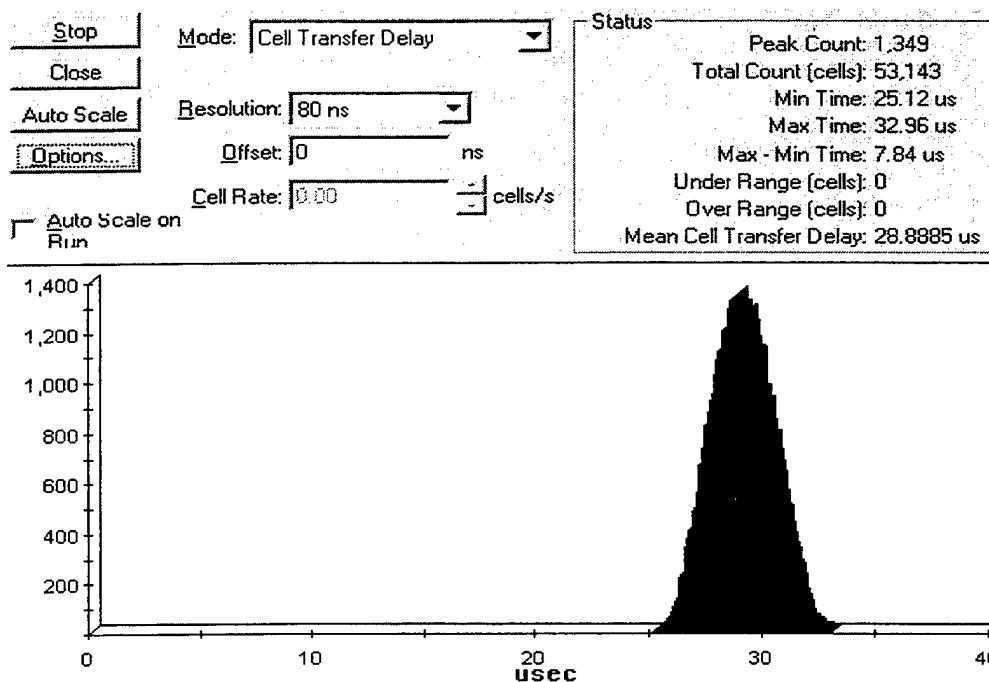
(a)
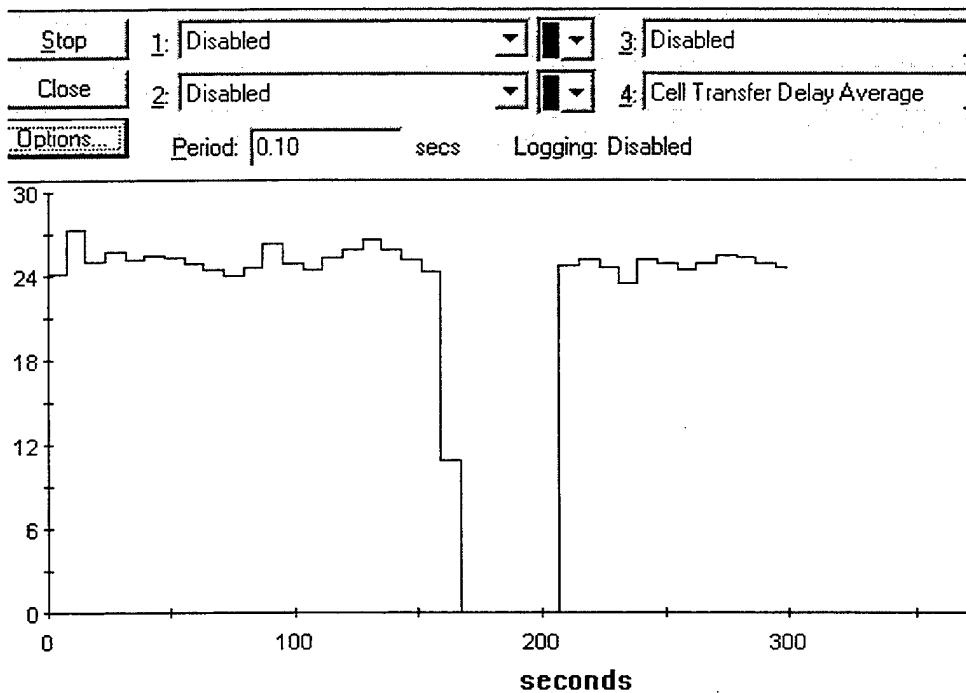
(b)

Figure B3 Cell Transfer Delay. (a) Histogram (b) Timescale.

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LIST OF REFERENCES

[1]   ATM forum, *UNI3.0 User Network Interface Specification,* Englewood Cliffs, New Jersey, Prentice Hall, Inc., 1993.

[2]   Li, S. Q. and Hwang, C. L., "Queue Response to Input Correlation Functions: Continuous Spectral Analysis," in *IEEE/ACM transactions on networking,* Vol.1, No.6, December 1993.

[3]   Li, S. Q. and Hwang, C. L., "Queue Response to Input Correlation Functions: Discrete Spectral Analysis," in *IEEE/ACM transactions on networking,* Vol.1, No.5, October 1993.

[4]   Lucas, M., Dempsey, B., Wrege, D., Weaver, A., "An efficient Background Traffic Model for Wide-Area Network Simulation," in *GLOBECOM 97 IEEE* Vol:3, pages 1572-1576.

[5]   Lucas, M., Dempsey, B., Wrege, D., Weaver, A., "Statistical Characterization of Wide Area IP traffic," in *Computer Communications and Networks, Sixth International Conference Proceedings,* Pages 442-447, 1997.

[6]   Jerkins, J. L., Wang, J. L., "Establishing Broadband Application Signatures through ATM Network Traffic Measurement Analysis," in *ICC 98. IEEE International Conference on Communication* Volume: 2, Page(s): 837 -843, 1998.

[7]   Sackett, G. C. and Metz, Y. C., *ATM and Multiprotocol Networking,* NY, McGraw-Hill, 1997.

[8]   Fore Systems, *Forerunner™ ATM Switch Network Configuration Manual,* MANU0148-03-Rev.A, pg. 1-397, 1995-1997.

[9]   Schwartz, M., *Broadband Integrated Networks,* Upper Saddle River, NJ: Prentice Hall, 1996.

[10]   Black, U., *ATM: Foundation for Broadband Networks,* Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 1995.

[11]   Michiel, H. and Leavens K., "Teletraffic Engineering in a Broad-Band Era," in *Proceedings of the EEE,* Vol.85, No.12, December 1997.

[12]   Hajek, B. and He, L., "On variations of Queue Response for Inputs with Same Mean and Autocorrelation Function," in *EEE/ACM Transactions On Networking,* Vol.6, No.5, October 1998.

[13] Li, S. Q. and Arifler, D., "SMAQ: A Measurement-Based Tool for Traffic Modeling and Queuing Analysis Part I: Design Methodologies and Software Architecture," in *IEEE Communications Magazine,* August 1998.

[14] Li, S. Q. and Kim, Y., "Timescale of Interest in Traffic Measurement for Link Bandwidth Allocation Design," in IEEE, 1996.

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